MANAGING WATER EXCESS AND DEFICIT IN AGRICULTURE

SUBSURFACE DRAINAGE AND IRRIGATION SYSTEMS



J.A. (JANINE) DE WIT

Propositions

1. Converting subsurface drainage systems to controlled drainage with subirrigation systems improves water management in the Netherlands.
   (this thesis)

2. Water system thinking ensures local hydrological measures fit catchment-wide characteristics.
   (this thesis)

3. Field pilots are essential for bridging scientific research and practical implementation.

4. A professional publication in a PhD thesis is necessary to reach policymakers.

5. Completing an external part-time PhD within 5 years requires prioritization and time management skills.

6. Seasonal vegetables play a too limited role in the Dutch dietary pattern.

7. Training for a marathon mirrors flexibility and endurance needed for long-term pursuits.

8. Individual efforts toward sustainable energy production contribute more to personal satisfaction than to society.

Propositions belonging to the thesis, entitled

Managing water excess and deficit in agriculture:
Subsurface drainage and irrigation systems

J.A. (Janine) de Wit
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Managing water excess and deficit in agriculture:

Subsurface drainage and irrigation systems

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Managing water excess and deficit in agriculture:

Subsurface drainage and irrigation systems

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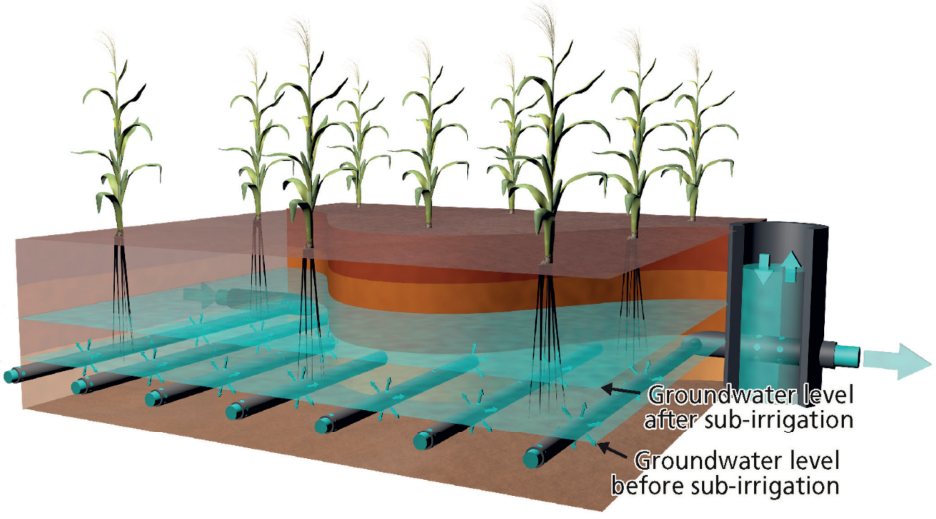
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Summary

"Your present circumstances don't determine where you can go, they merely determine where you can start" – Nido Qubei

Fresh water is needed worldwide for nature, agriculture and industrial activities. The water demand will increase in the future due to economic growth, urbanization, and food production, while freshwater supplies are decreasing. In addition, weather extremes (both more dry and more wet periods) will occur more frequently and more intensively due to climate change. Therefore, measures are necessary to anticipate the imbalance of water demand and supply. One of the measures could be to convert the historically existing drainage systems (in the Netherlands currently at approximately 34% of the agricultural fields) to controlled drainage with subirrigation (CDSI) systems to discharge, retain, and recharge water.

The Dutch water system has traditionally been designed to drain water efficiently to prevent flooding. Water is quickly drained from agricultural fields to surface water and then discharged from the area via canals and rivers. After World War II, the population growth led to an increase in food demand. Therefore, agricultural fields were drained with subsurface pipes to avoid too wet circumstances and thereby increase crop production. In addition to intensive drainage, land consolidation took place to enlarge agricultural fields and improve their accessibility. Pipe drainage, land consolidation, urbanization and groundwater extractions, among other things, caused a systematic decline in the groundwater levels. As a result, the agricultural fields in the Dutch Pleistocene uplands became more vulnerable for the effects of droughts. Parallel to the social-economical changes in society, pipe drainage systems also developed over time. Conventional pipe drainage aimed to discharge water, but developed into controlled drainage (CD) which aimed to both discharge and retain water. Nowadays, CD develops into controlled drainage with subirrigation (CDSI) with three aims: i) discharge water to avoid flooding or waterlogging, ii) retain water in the soil, and iii) recharge water to prevent agricultural and hydrological drought.



Controlled drainage with subirrigation. Figure is adapted from Narain-Ford et al. (2020).

In general, a CDSI system consists of a control pit where external water for subirrigation is supplied. The control pit is connected to a collector pipe, which is connected to the infiltration/drainage pipes perpendicular to the collector pipe. The control pit contains a small pipe which determines the maximal water level ('crest height'). A float can be used to control the water supply. If the hydraulic head in the control pit and drains exceeds the groundwater level, water flows through the pipes and infiltrates into the subsurface through the perforated pipe holes. As a result, groundwater level increases and soil moisture in the rooting zone of plants increases due to capillary rise from the groundwater. Internationally, countries as United States of America, Canada, Australia, Sweden and Iran have experience with CDSI.

In recent years, CDSI has been investigated as a technological measure to address the imbalance between water demand and water supply in the Dutch Pleistocene uplands. Four field pilots were conducted in America, Haaksbergen, Lieshout and Stegeren, which are all located on the higher sandy soils of eastern and southern Netherlands. The field pilots differed in soil profiles and geohydrological characteristics, but had similar measuring equipment. The field measurements show that CDSI raises groundwater levels, which increases the soil moisture content in the root zone through capillary rise. This increases water availability to the crop and thus increases plant transpiration and dry matter production. A simulation study with the Soil-Water-Atmosphere-Plant model (SWAP), calibrated to the field measurements, shows that only a minor part of the supplied water contributes to increased plant transpiration. Most of the supplied water leaves the system as ditch drainage and as downward seepage to the deeper groundwater. The distribution between these components largely depends on the adjacent surface water level and geohydrological characteristics.

The required water supply (subirrigation) was high in the field experiments, because a fixed and relatively high groundwater level was pursued throughout the growing season. The combination of a fixed crest level and the possibility of continuous water supply resulted in a water supply ranging between 500 and 1,000 mm per year. Water supply can be reduced by more smart water applications, whereby the CDSI system contains a dynamic crest level and a dynamic pump management. This allows an appropriate water level in the control pit on a daily basis, calculated via an algorithm based on actual soil moisture conditions and weather forecasts. A dynamically controlled CDSI system saves more water in a wet growing season with a small plant water deficit and herewith a relatively low water demand for subirrigation than in a drier growing season with a larger plant water deficit and therefore a relatively high water demand for subirrigation. Besides the active control of the CDSI system, water can also be saved if the resistance to downward seepage is higher (location characteristics), a higher ditch water level is maintained around an agricultural field or region (management) or a crop with deeper roots is cultivated (crop specific). Finally, this thesis shows that transpiration can increase (less transpiration reduction) through water supply and higher groundwater levels, but a situation may occur where more water is supplied while the transpiration remains equal. This means that the extra supplied water drains to the ditch or recharges regional groundwater system. Thus, in this situation, CDSI does not serve as a measure to increase crop production. The data obtained and SWAP-modeling procedure developed in this thesis can be used to determine the

effects of CDSI under different conditions, which supports CDSI implementation and management on field scale.

Although the water supply can be reduced through applying water in a smarter way, a CDSI system requires water, so this local measure affects the regional water system. Therefore, it is important that water system stakeholders agree on the extent to which CDSI can be applied. A system dynamics model (SDM) was built which is relatively easy to understand, but includes all key factors and non-linear interactions of a physical CDSI system. The SDM is based on the four field experiments and the calibrated SWAP model. In this SDM, CDSI is scaled in percentages of a total area where subirrigation is applied. As surface water is not infinitely available, the challenge is to balance water use for nature and across societal sectors. Results show that CDSI upscaling propagates non-linearities in hydrological fluxes, with three critical phases related to regional water availability determining the potential for successful CDSI upscaling. It is crucial to identify which phase the effects of upscaling correspond to: from Phase 1, with sufficient regional water availability; through Phase 2, a critical zone where water demand begins to limit regional availability; to Phase 3, where high water demand significantly impacts the regional water system and CDSI is no longer beneficial for the crop. All in all, CDSI could be one of the measures to consider for a climate robust soil-water system. However, CDSI, as a local measure, may increase pressure on surface water availability during drier periods. This requires embedding field measures such as CDSI into regional water management strategies.

The design, construction, and management of a CDSI-system should include the water quality of the water supply source to prevent clogging. Additionally, it is important to include stakeholders both for knowledge exchange as well as to build support for responsible implementation. Although the methodology in this study is applied to field experiments in the Netherlands, the modeling approach is generally applicable, allowing the analysis to be extended to other areas in the world.

As conclusion, historically, drainage systems were a measure for removing excess water. Therefore, drainage pipes were installed at approximately 34% of the Dutch agricultural fields. In the short term, it is a relatively small investment to convert traditional drainage systems to CD. In this way, the water strategy at these fields shifts from drainage to drainage when necessary and retention when possible, which is already a step towards a more climate robust soil water system. Then, if CDSI fits within the regional water management, water can be recharged. The effectiveness of CDSI systems depends, among other things, on the geohydrological characteristics (retention of water), meteorological and crop characteristics (water demand for subirrigation and effect on crop growth) and the implementation of CDSI within the regional water management (water availability for subirrigation).

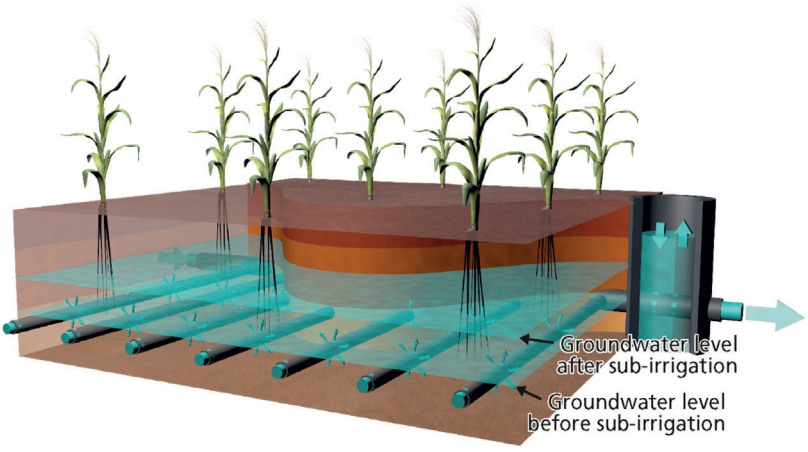
CDSI is one of the measures that can contribute to the transition towards a more climate-robust soil-water system in the Netherlands. In this transition period, there is a need to rethink the current landscape design, taking into account the physical interactions in the soil-water system. This might mean that geohydrological conditions are more leading in choices about land and water use, which could also mean accepting that not all types of

land use are feasible in every location at all times. For example, cultivate more drought-resistant crops in drier areas and cultivate more flood-tolerant crops in wetter areas. The measure CDSI could then be a technical measure to be used on agricultural fields where soil and water were leading in the decision to grow crops suitable for that location, but the field may still experience some dry and/ or wet periods, where CDSI could be used to mitigate the water stresses. The field experiments and related modeling approaches in this study have increased the hydrological understanding of CDSI, which can support decision-making regarding implementation by farmers and water management authorities.

Samenvatting

Water is een essentieel onderdeel van het dagelijks leven. Zoet water is onder andere noodzakelijk voor natuur, landbouw, drinkwater en industrie. De watervraag zal in de toekomst stijgen door onder andere economische groei, verstedelijking en benodigde voedselproductie, terwijl de beschikbaarheid van zoet water afneemt. Daarnaast zullen weersextremen (zowel drogere als nattere perioden) frequenter voorkomen door klimaatverandering. Hierdoor is er in toenemende mate een onbalans tussen watervraag en wateraanbod. Eén van de maatregelen om anders om te gaan met water in de landbouw is het aanpassen van de huidige drainagesystemen, die op al ongeveer 34% van de landbouwpercelen liggen.

Het Nederlandse watersysteem is van oudsher ingericht op het afvoeren van water met als doel wateroverlast te voorkomen. Hierdoor wordt water snel afgevoerd van de percelen naar het oppervlaktewater en via het oppervlaktewater uit het gebied. Na de Tweede Wereldoorlog nam de bevolkingsgroei toe, waardoor ook de voedselvraag toenam. Daarvoor zijn landbouwpercelen intensiever ontwaterd door de aanleg van buisdrainage om te natte omstandigheden te voorkomen en hiermee de gewasproductie te verhogen. Naast intensievere ontwatering vond er ook ruilverkaveling plaats om landbouwpercelen te vergroten en beter bereikbaar te maken. Buisdrainage, ruilverkaveling, verstedelijking en grondwateronttrekkingen hebben samen voor een systematische daling van het grondwaterniveau gezorgd, waardoor agrarische percelen op de hoge zandgronden kwetsbaarder zijn geworden voor de gevolgen van droogte. Parallel aan de sociaaleconomische veranderingen, ontwikkelde ook de buisdrainage zich verder. Conventionele buisdrainage is gericht op water afvoeren, maar ontwikkelde zich naar regelbare drainage (RD) gericht op zowel het afvoeren als vasthouden van water. Meer recent ontwikkelde RD naar regelbare drainage met subirrigatie (RDS) dat drie doelen kan dienen: i) water afvoeren wanneer nodig, ii) water vasthouden wanneer mogelijk en iii) (grond)water aanvullen.



Regelbare drainage met subirrigatie. Figuur is overgenomen van Narain-Ford et al. (2020).

RDS bestaat over het algemeen uit een regelput waar uit een externe bron water aan wordt toegediend. In de regelput bevindt zich een eenvoudige pvc pijp of een balg, dat het maximale waterniveau bepaalt (‘cresthoogte'). Met een vlotter kan de wateraanvoer worden geregeld. De regelput is verbonden met een verzamelleiding, die weer verbonden is met drains die loodrecht op de verzamelleiding liggen. Bij een stijghoogte in de put en de drains die hoger is dan de grondwaterstand, vindt er infiltratie plaats. Internationaal gezien, is er in landen als Amerika, Canada, Australië, Zweden en Iran ook ervaring opgedaan met RDS.

In de afgelopen jaren is RDS onderzocht als maatregel om te anticiperen op de onbalans tussen watervraag en wateraanbod in landbouwpercelen op de Nederlandse hoge zandgronden. Vier veldproeven zijn uitgevoerd in America, Haaksbergen, Lieshout en Stegeren, gelegen in Oost- en Zuid-Nederland. De vier veldproeven verschillen in geohydrologische kenmerken en de wateraanvoerbron van subirrigatie, maar zijn vrijwel identiek ingericht met meetapparatuur. De veldmetingen laten zien dat, als gevolg van RDS, het grondwaterpeil stijgt, waardoor het bodemvochtgehalte toeneemt door capillaire opstijging naar de wortelzone. Dit verhoogt de waterbeschikbaarheid voor het gewas en daarmee de transpiratie (gewasverdamping) en drogestofproductie. Een modelstudie met het Soil-Water-Atmosphere-Plant model (SWAP), gekalibreerd aan metingen, laat zien dat, afhankelijk van het oppervlaktewaterniveau en de geohydrologische gebiedskenmerken, slechts een klein deel van het aangevoerde water naar transpiratie van het gewas gaat, een deel van het aangevoerde water naar de aanliggende sloot stroomt (= slootdrainage) en een deel van het aangevoerde water naar het diepere grondwater (= wegzijging) stroomt. Een hogere weerstand tegen wegzijging voorkomt dat het geïnfiltreerde water snel wegsijpelt naar het diepere grondwater. Een hoger oppervlaktewaterniveau, aangepast aan de hogere grondwaterstand, zorgt voor minder drainage naar de sloot.

De benodigde wateraanvoer was hoog tijdens de veldproeven doordat er in het groeiseizoen continu werd gestreefd naar een vast en relatief hoog grondwaterniveau. Bij de combinatie van een vast crest niveau en de mogelijkheid tot continue wateraanvoer varieerde de wateraanvoer tussen 500 mm en 1.000 mm per jaar. De benodigde hoeveelheid water voor subirrigatie kan aanzienlijk verlaagd worden door ‘slimmer’ water aan te voeren. Het RDS systeem bevat dan een dynamisch crest niveau en een dynamische pompsturing om een passend waterniveau in de regelput per dag in te stellen. Het waterniveau wordt berekend met een algoritme gebaseerd op actuele gewasbehoefte, actuele waterbeschikbaarheid en weersverwachting. Dynamische sturing bespaart meer water in nattere groeiseizoenen met een gering watertekort voor de plant en hiermee ook relatief geringe watervraag voor subirrigatie dan in drogere groeiseizoenen met een groter watertekort en grotere watervraag. Naast actief sturen, kan er ook nog water bespaard worden als de weerstand tegen wegzijging groter is (locatiegeschiktheid), een hoger slootpeil wordt gehandhaafd rond het perceel of in de regio (beheer), of een gewas met diepere wortels wordt geteeld (gewaskeuze). Tot slot blijkt uit deze studie dat door wateraanvoer en hogere grondwaterstanden en bodemvochtgehaltes de transpiratie kan stijgen (minder verdampingsreductie), maar dat de situatie kan ontstaan waarbij extra aangevoerd water niet meer leidt tot hogere transpiratie, maar het extra aangevoerde

water draineert naar de sloot of het regionale grondwatersysteem aanvult via wegzijging. De verkregen metingen en de ontwikkelde SWAP procedure in dit proefschrift kunnen worden gebruikt om de effecten van RDS onder verschillende geohydrologische karakteristieken te bepalen, wat de implementatie en beheer van RDS op veldschaal ondersteunt.

Ondanks dat de wateraanvoer verminderd kan worden door meer gericht water aan te voeren, vraagt RDS om water waardoor deze lokale maatregel ingepast moet worden in het regionale watersysteem. Het is daarom belangrijk dat belanghebbenden van het watersysteem het eens zijn over de mate waarin RDS kan worden toegepast en kan worden gefaciliteerd. In deze studie is een systeem dynamisch model opgezet dat relatief eenvoudig te begrijpen is, maar dat alle belangrijke aspecten en niet lineaire interacties bevat van een RDS-systeem. Daarbij is het model gebaseerd op kennis van de uitgevoerde veldproeven en SWAP-modellering. In het systeem dynamisch model is RDS opgeschaald in percentages van een totaal gebied waarop het wordt toegepast. Oppervlaktewater is niet oneindig beschikbaar, waardoor de uitdaging is om water op een evenwichtige manier te gebruiken en te beheren, zowel voor verschillende maatschappelijke sectoren als voor natuur. Opschaling van subirrigatie laat drie toestanden zien: 1) er is voldoende oppervlaktewater beschikbaar om RDS op te schalen naar een groter gebied, waarbij het oppervlaktewaterniveau op peil blijft, 2) er is voldoende oppervlaktewater beschikbaar om RDS op te schalen, maar het slootpeil daalt sterk, wat impact heeft op de regionale waterbeschikbaarheid en 3) er is onvoldoende oppervlaktewater beschikbaar om RDS op te schalen, wat resulteert in een te laag oppervlaktewaterpeil, een hogere watervraag voor subirrigatie en uiteindelijk weinig effect van subirrigatie op de waterbeschikbaarheid voor gewassen. Oftewel, RDS kan bijdragen aan de waterbeheerstrategie op regionale schaal, maar verhoogt ook de druk op het oppervlaktewater, dat veelal beperkt beschikbaar is. Het systeem dynamisch model kan gebruikt worden om te verkennen of en in welke mate RDS opgeschaald kan worden in een gebied in relatie tot de beschikbaarheid van oppervlaktewater en welke aspecten hiervoor bepalend zijn.

Bij het ontwerp, de aanleg en het beheer van een RDS moet rekening worden gehouden met de waterkwaliteit van de subirrigatiebron om verstopping te voorkomen. Tot slot is het belangrijk om alle belanghebbenden van het watersysteem betrokken te houden voor zowel kennisuitwisseling als uiteindelijk een groter draagvlak voor implementatie. Hoewel de methoden zijn toegepast op veldexperimenten in Nederland, zijn de modellen algemeen toepasbaar, waardoor de analyse kan worden uitgebreid naar andere regio's in de wereld.

Concluderend, drainage is een historische maatregel om water te draineren, waardoor het al in 34% van de Nederlandse landbouwpercelen ligt. Op korte termijn is de omvorming van traditionele systemen naar regelbare drainage een relatieve lage investering, waarbij wel de water strategie verandert naar water afvoeren wanneer nodig en water vasthouden wanneer mogelijk. Als vervolgens ook RDS in het regionale waterbeheer past, kan ook het grondwater aangevuld worden. De effectiviteit van RDS systemen voor zowel verbeterde omstandigheden voor gewasgroei als het aanvullen van het regionale grondwatersysteem wordt bepaald door geohydrologische condities (water kunnen vasthouden),

meteorologische condities en gewaskenmerken (watervraag naar subirrigatie en effect op gewasgroei) én de inpassing van CDSI in het regionale oppervlaktewatersysteem (en hiermee de waterbeschikbaarheid voor subirrigatie).

RDS is één van de maatregelen die kan bijdragen aan de transitie naar een klimaat-robuust bodem-water systeem in Nederland. In deze overgangsperiode zou de inrichting van het landschap moeten worden heroverwogen, rekening houdend met de fysische mogelijkheden en beperkingen van het landschap. Dit kan betekenen dat geohydrologische omstandigheden een leidende rol gaan spelen bij keuzes over land- en watergebruik. Daarbij is het mogelijk dat niet alle vormen van landgebruik overal en altijd haalbaar zijn. Dit kan resulteren in de keuze voor meer droogteresistente gewassen in drogere gebieden en gewassen die beter bestand zijn tegen wateroverlast in nattere gebieden. De maatregel RDS kan dan worden gezien als technische oplossing die wordt toegepast op landbouwpercelen waar bodem en water leidend waren in de keuzes voor de gewassenteelt die geschikt zijn voor die locatie, maar waar het perceel toch nog te maken heeft met te droge en/of natte perioden. RDS zou dan kunnen worden ingezet om waterstress te mitigeren. Dit onderzoek heeft de inhoudelijke kennisbasis over RDS vergroot, en kan bijdragen aan de besluitvorming over het al dan niet toepassen van de maatregel door agrariërs en waterbeheerders.

List of symbols

A_{ditch}	Size ditch	[L^2]
A_{pit}	Size area pit	[L^2]
A_{sub}	Size area subirrigation	[L^2]
CR	Capillary rise to rootzone	[L^3]
DP	Percolation to groundwater	[L^3]
Dr_{rz}	Depth rooting zone	[L]
DS	Seepage or upward flow from groundwater	[L^3]
ET_{act}	Actual evapotranspiration	[L]
ET_{ref}	Reference evapotranspiration	[L]
ET_{pot}	Potential evapotranspiration	[L]
H_{crest}	Height of the fixed or online controlled weir (crest) in the pit	[L]
H_{ditch}	Water level in the ditch	[L]
H_{pit}	Water level in the control pit	[L]
GWL	Groundwater level	[L]
GWL_{pref}	Preferable GWL	[L]
MHG	Mean highest groundwater level	[L]
MLG	Mean lowest groundwater level	[L]
MSL	Mean sea level	[L]
P	Precipitation	[L]
Q_{area_in}	Regional inflow	[L^3]
Q_{area_out}	Regional outflow	[L^3]
Q_{ditch}	Ditch drainage	[L^3]
Q_{pipe_drain}	Pipe drainage	[L^3]
Q_{pipe_inf}	Pipe infiltration	[L^3]
Q_{pit_out}	Outflow of the control pit	[L^3]
Q_{pond}	Ponding layer	[L^3]
Q_{weir_in}	Inflow over the weir	[L^3]
Q_{weir_out}	Outflow over the weir	[L^3]
$Q_{subirri}$	Water used for subirrigation	[L^3]
S	Storage coefficient	[-]
SMC	Soil moisture content	[L^3/L^3]
SWP	Soil water potential	[M]
$\theta_{\mathbf{rz}}$	Volumetric soil moisture content in the rooting zone	[L^3/L^3]
$\theta_{\mathbf{sat}}$	Volumetric saturated soil moisture content	[L^3/L^3]
$\theta_{\mathbf{wp}}$	Volumetric soil moisture content at wilting point	[L^3/L^3]
WL_{ditch}	Ditch water level	[L]
WL_{pit}	Water level in the control pit	[L]
W_{supply}	Water supply	[L^3]

List of abbreviations

CAD	Climate adaptive drainage
CAD-MA	Climate adaptive drainage management algorithm
CD	Controlled drainage
CDSI	Controlled drainage with subirrigation
CDSI-dyn0	Controlled drainage with subirrigation with a dynamic crest height in the control pit and accepting 0% oxygen and drought stress
CDSI-dynX	Controlled drainage with subirrigation with a dynamic crest height in the control pit and accepting X% oxygen and drought stress (10, 20, 30, 40%)
CDSI-fix	Controlled drainage with subirrigation with a fixed crest height in the control pit
CV	Coefficient of variation
EU	European Union
KNMI	Royal Netherlands Meteorological Institute
KGE	Kling-Gupta efficiency
Lay2	Second layer of the unsaturated zone
RMSE	Root mean square error
RSR	Root mean square error-observations standard deviation ratio (normalized RMSE)
SDM	System dynamics model
ss	Soil surface
SWAP	Soil Water Atmosphere Plant model
PEST	Model-Independent Parameter Estimation and Uncertainty Analysis software
WWTP	Wastewater treatment plant

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1

CHAPTER 1

INTRODUCTION

1 Introduction

1.1 European freshwater management

Fresh water is essential for human and ecosystem needs and plays an important role in the economy. In Europe, most water is used in the industry (55%), agriculture (29%) and domestic sectors (16%) (Flörke et al., 2013). The total water use varies in different European Union (EU) regions, depending on several factors including geographical location, population growth, living standards, climate patterns and efficiency of water management (Mariolakos, 2007). However, the freshwater demand is expected to increase due to e.g. economic growth, urbanization and food production, while the water availability is expected to decrease (Rodell et al., 2018). At the same time, weather extremes are expected to occur more frequently and to become more extreme due to climate change (Spinoni et al., 2019; Teuling, 2018). Because of these (climate) changes, there is an increased mismatch between water demand and water supply (Pronk et al., 2021) intensifying the effects of droughts (Bevacqua et al., 2024).

Fresh water transcends national boundaries making it important to streamline freshwater directives on a European scale to protect water quantity and quality and ensure long-term sustainable water use. Therefore, freshwater management policies are increasingly embedded in the economic development policies of the EU and in policies of each individual EU country (Ziolkowska and Ziolkowski, 2016). Nowadays, two important legislative frameworks are established to protect and manage fresh and salt water resources in Europe: Water Framework Directive (in Dutch: Kaderrichtlijn Water, KRW) and Framework Directive Marine Strategy both supported with specific water guidelines (European Commission, 2024). European freshwater management policies contribute to achieving the climate adaptation and mitigation goals of the Paris Agreement, and align with the defined Sustainable Development Goals: a set of 17 global goals aimed at creating a more sustainable world by 2030 (Griggs et al., 2013). All countries are responsible for achieving their goals.

Freshwater management challenges vary throughout Europe depending on several factors including climate and geohydrological characteristics. Most northern, central and western European countries have relatively shallow groundwater levels and a rain-fed agricultural production whereas the Mediterranean countries have relatively deep groundwater levels in which irrigation, extracted from groundwater or reservoirs, plays a key role (Chávez García Silva et al., 2024). Other important differences within Europe include soil characteristics such as peaty, clayey or sandy soils, as well as the presence of rocks in the subsoil, and whether areas are low-lying and flat or high and hilly. In addition, parts of Europe are deltas affecting the (surface) freshwater management (Nolf et al., 2021), such as the Netherlands. Depending on the specific challenges of a country, specific goals can be defined and translated into measures. In this thesis I focus on the Netherlands where one of the national goals is to develop a climate-resilient and water-robust country in 2050 (Ministry of Infrastructure and Water Management et al., 2022).

1.2 Dutch freshwater management

1.2.1 Dutch freshwater management in various programs

The Netherlands is a low-lying country, located in a delta in the Western part of Europe, which continuously fights against water (Blankesteijn and Pot, 2024; Van Stokkom et al., 2005). The Dutch water governance dates back to the 8th century (Van de Ven, 2003). The challenge to live in the Dutch delta has been addressed in various programs over the last decades. Traditionally, several hydraulic engineering techniques as dikes and dams have been built in the Netherlands to protect the inhabitants for water. However, in February 1953 the dikes in the southwest of the Netherlands broke with disastrous consequences (Gerritsen, 2005). A 'Deltacommission' was established to come up with an advice on flood protection along the coast (Advice first Deltacommission, 1960). Later, in 1995, the water levels in the rivers were so high that more than 200,000 inhabitants of areas along the Dutch rivers Rhine and Meuse were evacuated (Chbab, 1995). This resulted in the flood policy program 'Room for the River' in 2006 (Zevenbergen et al., 2015). Conversely, the Netherlands experienced a drought in 2003 (Van Duinen et al., 2015).

The Dutch water system was unable to cope with the existing and upcoming challenges as droughts and floods at the beginning of the 21st century. Therefore, Deltacommissions were established in more frequent form in the 21st century than in the 20th century to ensure a liveable Dutch delta, now and in the future (Deltacommission, 2008). In 2008, the second 'Deltacommission' was established, which was not focused on a particular disaster, but was asked to advise on envisioned water threats for the Netherlands (Deltacommission, 2008). In line with Advice of the 21st century Water Management Committee (2000) their main recommendation was to increase the flood protection levels of the dykes and a shifting water management strategy of i) retention of water, ii) recharge of water and iii) discharge of water (Deltacommission, 2008) (Figure 1.1-III).

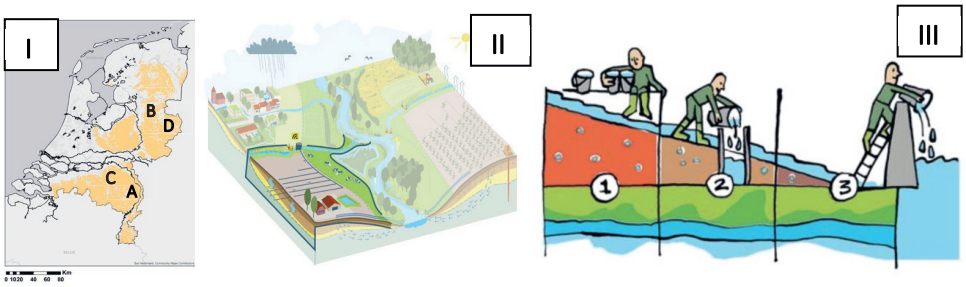


Figure 1.1: The Netherlands with the (drought sensitive) sandy Pleistocene uplands (yellow) (± 0 – 100 m+MSL). The letters A, B, C and D represent the locations of the field experiments used in this thesis (I). The figure is adapted from De Wit et al. (2024c). The main focus in this thesis is the agricultural area. Figure is adapted from Lumbricus - Bartholomeus (red.) (2021) (II). A resilient soil-water system should focus on water retention (1), water recharge (2) and water discharge (3). Figure is adapted from Advice of the 21st century Water Management Committee (2000) (III).

From the 21st century onwards, the main focus became increasingly on water discharge, retention and recharge, but also to adapt land use to the preferred water management (National Deltaprogram, 2014; National Deltaprogram, 2019). However, the Netherlands encountered extreme drought events in 2018 – 2020 and 2022, which are expected to occur more frequently (Philip et al., 2020). Furthermore, in July 2021 an extreme flood event occurred in the border region of the Netherlands, Germany and Belgium (Kreienkamp et al., 2021; Tradowsky et al., 2023). In addition, the most recent climate scenarios for the Netherlands indicate that multi-year drought events will occur more frequently (Van der Wiel et al., 2023). Therefore, the current challenge is to design a resilient soil-water system that can anticipate both (extremely) wet and dry periods (Ministry of Infrastructure and Water Management et al., 2022). In 2022, the policy letter 'Water and soil leading in land use planning' was written which focused on land use adapted to the natural land and water conditions (Ministry of Infrastructure and Water Management, 2022). As a result, it seemed that there was a shift to a more nature-based water management (Bartholomeus et al., 2023). Nowadays, water management is attenuated towards solutions in spatial planning and should deal with both too much and too little water (National Deltaprogram, 2024).

1.2.2 Shifting Dutch freshwater management strategy

Parallel to several water programs in the last century there have been major changes in water management mainly triggered by land use changes as consequence of social and economic changes. After World War II, population growth resulted in extensive urbanization. The paved urban area doubled in the western part of the Netherlands since 1945 (Advice of the 21st century Water Management Committee, 2000). Population growth caused urbanization but also increased the food demand. Therefore, agricultural fields were intensively drained (conventional drainage) to lower groundwater levels and thereby increasing crop production (Ritzema and Stuyt, 2015). The main Dutch freshwater challenge in the 20th century was to drain water more quickly with the result that, in 2012, 34% of the Dutch agricultural land was drained (Massop and Schuiling, 2016). In addition to drainage, land consolidation took place with the aim of adapting fields to more efficient cultivation (e.g. larger fields, fields closer to a farm) (Molema and van den Brink, 2009; Van den Noort, 1987). Besides larger agricultural fields, the landscape view also changed. Landscape elements such as smaller ditches, wooded banks, groves, curved fields and unpaved roads changed to paved roads and larger ditches (Vitikainen, 2004).

Major changes in pipe drainage, land consolidation, urbanization and groundwater extraction have led to systematically lower groundwater levels, which have declined by an average of 50 cm in the higher sandy soils during the 20th century (Knotters and Jansen, 2005). The combination of freshwater needs for society and nature, declining groundwater levels, and climate change has led to an increased mismatch between water demand and water supply (Pronk et al., 2021). However, in many areas the water system is not designed to anticipate weather extremes and to cope with the imbalance in water demand and water supply. Therefore, in temperate climates like the Netherlands, the water strategy is changing on both local and regional scales from drainage to drainage and retention, or

even to drainage, retention and recharge (Bartholomeus et al., 2023; De Wit et al., 2022) (Figure 1.1).

1.2.3 Freshwater challenges in the Dutch Pleistocene uplands

The Netherlands can be split into a lower part (peat and clay soils in the west, grey areas in Figure 1.1-I) and a higher part (sandy soils in the southeast, yellow areas in Figure 1.1-I). In this thesis, I focus on the higher sandy soils, also called the Dutch Pleistocene uplands (Figure 1.1-I, II). The Dutch Pleistocene uplands are water-limited areas as they are mainly rainfed and the cumulative potential rainfall deficit in the growing season ranges between 120 mm for meteorologically average years to more than 300 mm for dry years (Klein Tank et al., 2014). Thereby, only 40% of the sandy soils get water from the main Dutch water system (National Deltaprogram, 2014). Furthermore, the combination of intensified drainage from the 20th century, increased groundwater extractions and the characteristic that sandy soils have a small water holding capacity makes them sensitive to droughts. Conversely, extreme rainfall could lead to wet circumstances or flooding.

Too wet or too dry conditions influence crop growth. Crop growth depends, among other things, on soil moisture availability. Soil moisture availability is mainly affected by precipitation, evapotranspiration, the groundwater table (via percolation and capillary rise) and soil hydraulic characteristics. The combination of low precipitation and high evapotranspiration may result in a too deep groundwater level (*GWL*) for capillary rise to reach the root zone, which increases plant water stress and reduces crop yield. Additionally, the interaction between the *GWL* and surface water level (H_{ditch}) determines ditch infiltration ($GWL < H_{ditch}$) and ditch drainage ($GWL > H_{ditch}$), thus influencing groundwater levels. The interaction between the *GWL* and hydraulic head in deep groundwater aquifers determines upward or downward seepage. Surface water levels can be managed through weirs and external water supply (regional water management). So, the local and regional water systems are highly interconnected (Figure 1.2).

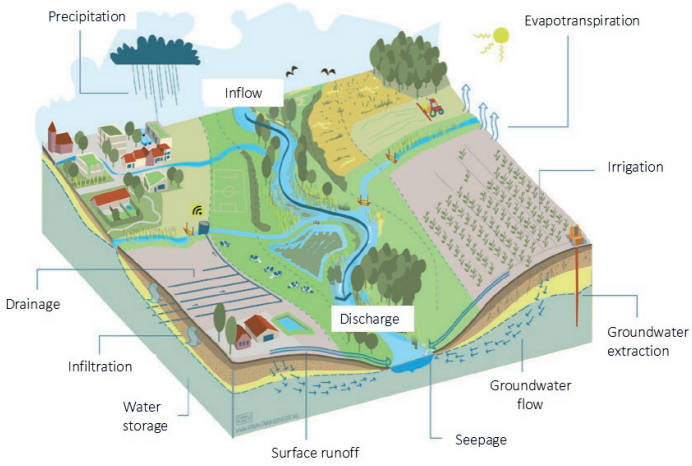


Figure 1.2: Landscape overview with main components of the regional water balance. Figure is adapted from Lumbricus (Bartholomeus (red.), 2021).

The current landscape design, the drought-sensitive characteristics in the Dutch Pleistocene uplands, the mismatch in water demand and water supply, and an increase in weather extremes imply that the Dutch Pleistocene uplands need to become more climate-resilient and water-robust. Therefore, in addition to the national-scale freshwater program, regional programs have been established. From 2015, several regional programs have been set up focused on collaboration between water management authorities, farmers, municipalities, industries, provinces and research institutes. These programs focused on measures to anticipate dry and wet conditions as within Lumbricus (www.stowa.nl/lumbricus) and KLIMAP (www.klimap.nl). The programs clearly showed that in order to move forward to a more climate-robust environment, it is essential to have knowledge about both technical details of measures, their impact on local and regional freshwater availability and which governance arrangements are needed to implement measures.

1.3 Subsurface drainage with subirrigation as measure in the Dutch Pleistocene uplands

The Dutch Pleistocene uplands appear to be uniform, but subtle differences occur in, among other things, soil characteristics, water management and relative height in the landscape. Therefore, a 'toolbox' with different measures is increasingly necessary to develop a climate-robust water system in the Netherlands, and to anticipate the imbalance of water demand and water supply[1]. Short-term measures can often be taken relatively quickly and easily, but might show limited effectiveness in the long term. Examples of measures for drought could be sprinkler irrigation for crops, water supply from other areas or water retention using small weirs (Van den Eertwegh et al., 2021). Conversely, long-term measures could better anticipate extreme weather events, both wet and dry periods, but are often more difficult to implement (Van den Eertwegh et al., 2021), for example changes in spatial planning (National Deltaprogram, 2024). Additionally, adaptation measures for wet circumstances can make areas more vulnerable to drought and vice versa (Bartholomeus et al., 2023). Therefore, for each measure it must be clear how a measure contributes to wet and dry circumstances, on what time scale it can be implemented and what it means for the regional water system. In this thesis, I focus on the hydrological effects of the measure subsurface drainage systems with subirrigation in agriculture.

Subsurface drainage is applied worldwide to make areas suitable for agriculture. This happened in the Netherlands from the 10th century onwards (Haartsen et al., 2010; Stuyt, 2013). Parallel to the changing water strategy and various water programs (section 1.2.3), there was a further development of subsurface drainage systems from the 20th century onwards. Conventional drainage consisting of single drainage pipes in the subsurface discharging groundwater to ditches, were modified to controlled drainage (CD), in which the water pressures in the pipes could be controlled through controlling the water level in a ditch by a weir. Later on, CD was modified to composite controlled drainage, where the

[1] https://www.deltaprogramma.nl/gebieden/hoge-zandgronden/maatregelen

single drain pipes were connected to one collector pipe, connected to a control pit, which on his turn was connected with the adjacent ditch. More recently the control pit was also used for water infiltration: by pumping water into the control pit, water recharges the groundwater through the drainage pipes (Figure 1.3). The last modification is called controlled drainage with subirrigation (CDSI) which can be used to i) discharge, ii) retain, and iii) recharge water. The development of drainage systems is described in more detail in Chapter 2.

Converting subsurface drainage systems to drainage with subirrigation systems affects both agricultural practices and regional water management. Drainage systems are installed on agricultural fields and therefore farmers are the primary users of the system. The goal of using a CDSI system with subirrigation is to raise the *GWL* so that the soil moisture availability increases, which raises the crop yield. However, an external water source is needed for subirrigation, for example surface water from an adjacent ditch or effluent from an industry. In the Netherlands, surface water and herewith the regional water management in the rural area is managed by water management authorities. So, if surface water is used for subirrigation, water management authorities should understand how field scale CDSI fits within the regional water system. Although converting CD systems to CDSI systems is included in the national program as measure to create climate-robust Dutch Pleistocene uplands (National Deltaprogram, 2021), it is relatively unknown in practice. This causes a lack of knowledge in understanding how CDSI systems technically work and how the hydrological effects of CDSI propagate through the local and regional water system. Therefore, in this thesis I focus on the hydrological possibilities and limitations of local and regional implementation of CDSI in the Pleistocene uplands of the Netherlands.

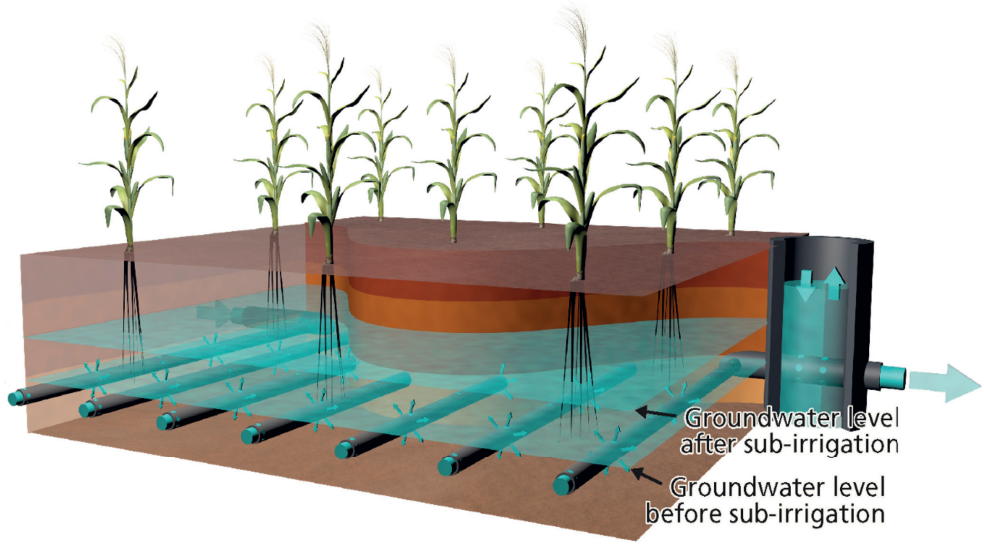


Figure 1.3: Subsurface drainage with subirrigation. Figure adapted from Narain-Ford et al. (2020).

1.4 Objectives

Sufficient freshwater is required for the needs of both human and ecosystems, and water plays an important role in the economy. However, even in the low-lying Dutch delta an increasing mismatch occurs between water demand and water supply. The combination of a water management focused on drainage, low groundwater levels and a changing climate increases the impact of droughts in the Dutch sandy Pleistocene uplands, while still being vulnerable to floods in periods of heavy rainfall. Therefore, the water management strategy is shifting towards water discharge when needed, water retention where it precipitates and water recharge when needed and possible. One of the measures for this is further development of subsurface drainage systems, which traditionally exist in the Netherlands, to drainage with subirrigation systems. However, this requires understanding of how CDSI systems technically work and how the hydrological effects of CDSI propagate through the local- and regional water system. The main research question of this thesis therefore is:

What are the hydrological opportunities and limitations for implementing controlled drainage with subirrigation at local and regional scales in the Dutch Pleistocene uplands?

The following sub-research questions are formulated to answer this main research question:

1. *How have subsurface drainage systems developed in the 20th century, including their corresponding drainage strategies and the consequences for the groundwater and surface water system?*
2. *What are the hydrological consequences of subirrigation and how can these consequences be simulated using a field scale agro-hydrological model?*
3. *To what extent could external water supply for subirrigation be reduced by automatic control of CDSI systems in relation to crop water demand?*
4. *To what extent can regional upscaling of CDSI be supported with available surface water and how can an SDM support water management authorities in decision-making?*

The research questions were answered by successively conducting a literature study, field experiments and modelling (at local and regional scales) (Figure 1.4). First of all, an international literature study has been conducted to investigate developments in history as well as the scientific status of current drainage systems. Secondly, field experiments with CDSI systems and their modelling analysis were conducted to investigate the hydrological consequences of CDSI systems on field scale in the Netherlands. Thirdly, the modelling studies of the second step have been further developed to optimize the field scale operational use of CDSI systems. Lastly, the knowledge of the literature study and field scale modelling was used to model regional upscaling of subsurface irrigation to support decision-making by regional water management authorities. The field pilots and different modelling approaches are explained in more detail in section 1.5.

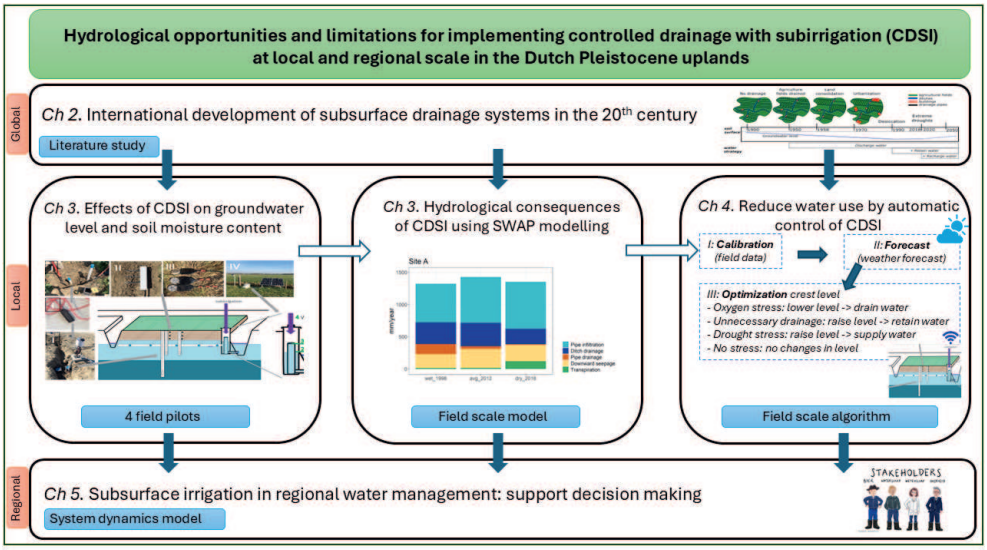


Figure 1.4: Structure of this study including chapter numbers (ch + number), methods (blue) and scale (orange).

1.5 Outline thesis

The chapters in this thesis are structured as illustrated in Figure 1.4. The development of subsurface drainage system in the 20th century is described in Chapter 2. Literature is used to provide insight into the shifting water management strategy in the Netherlands (1950-2020) with corresponding drainage strategy. Furthermore, we provide insight in the effect of subirrigation on groundwater levels and crop yields, based on both international literature and measurements of Dutch field pilots.

The hydrological consequences of controlled drainage with subirrigation are analysed in Chapter 3. Four CDSI field pilots (Figure 1.5) with varying geohydrological conditions were monitored (minimum 5 years) to study the effects on groundwater level, soil moisture content and soil water potential. Furthermore, the field scale agro-hydrological Soil, Water, Atmosphere, Plant (SWAP) model (Heinen et al., 2024; Kroes et al., 2017), calibrated with PEST, was used to quantify all water balance components for the field pilots. Key in the presented modelling approach and an important improvement to earlier modelling approaches of CDSI, is that both the water supply rates and the water and crest levels in the control pit of CDSI were simulated dynamically. Both the results of the field monitoring and modelling are given for all four field locations.

Chapter 4 deals with to what extent it is possible to reduce external water supply for subirrigation by the control of CDSI systems in relation to crop water demand. The SWAP model is used to simulate the optimal drainage level and day by day water demand and supply. A major improvement is that both crest level and water supply of CDSI are dynamically controlled taking into account plant water demand, the actual soil moisture conditions and the weather forecast, in contrast to a fixed approach which focusses on maintaining a specific 'fixed' groundwater level. The results show the hydrological

consequences of a dynamic approach compared to a fixed approach, including the impact of geohydrological and crop characteristics and the acceptance of minor drought stress.

The effects of upscaling of CDSI systems to regional hydrological fluxes are described in Chapter 5. Hydrological models vary in scale, complexity and objectives: from spatially distributed models as Mike She (www.dhigroup.com) to lumped models as Walrus (Brauer et al., 2014), HBV (Bergström, 1995) WEAP (www.weap21.org), to black-box models (Devia et al., 2015). Also, soil, water, plant models as Hydrus (Šimunek and Šejna, 2018), Daisy (www.daisy.ku.dk), AquaCrop (Raes et al., 2023) have all a slightly different focus either with or without a crop module as WOFOST (De Wit et al., 2020). One type of a lumped model is a system dynamics model (SDM) which is widely applied to understand non-linear behavior of complex systems with feedback-driven components that must be understood in order to make policy decisions and design (Mashaly and Fernald, 2020). A lumped SDM is designed such that it is transparent, which makes it relatively easy to understand the system and the impacts of management scenarios (Khan et al., 2009). Subsystems and interactions can easily be added. However, it should always be considered whether adding complexity contributes to improved understanding and simulation accuracy (Wagener et al., 2001). In water resources management, SDMs are mostly applied as rainfall-runoff model, but minimally applied for groundwater modeling (Phan et al., 2021). We build a lumped SDM to simulate changes in hydrological fluxes and water levels when CDSI is scaled up from local to regional scale. The results show how upscaling possibilities of subirrigation depend on regional surface water management, crop characteristics, groundwater level requirements and field characteristics. The results could support water management authorities i) to investigate to what extent regional upscaling of CDSI can be supported with available surface water, and ii) in their decision-making.

The synthesis of this thesis (Chapter 6) contains the main findings in terms of hydrological opportunities and limitations of CDSI as supported by the analysis in this thesis. Additionally, I elaborate on how CDSI could contribute to a climate-robust soil-water system. This includes the conclusion of this thesis, in which nine requirements for CDSI are described to support practical implementation. The section is followed by findings from associated research and recommendations for further research. The thesis is concluded with how to bring CDSI from science to practice and society, including stakeholder engagement.



Figure 1.5: Impression of the field experiment in America (I; location A in Figure 1.1-I) and Stegeren (II, III; location B in Figure 1.1-II).

2

CHAPTER 2

DEVELOPMENT OF SUBSURFACE DRAINAGE SYSTEMS: DISCHARGE – RETENTION – RECHARGE

This chapter is based on the publication:

De Wit J.A., Ritsema C.J., van Dam J.C., van den Eertwegh G.A.P.H., Bartholomeus R.P. (2022) Development of subsurface drainage systems: Discharge – retention – recharge. Agricultural Water Management 269:107677. DOI: https://doi.org/10.1016/j.agwat.2022.107677

Highlights

- Use of drainage systems shifted from discharge to retention and recharge
- Subirrigation positively affects crop growth, but water supply could be large.
- Implementation of subirrigation requires an integral, catchment-wide approach.

Abstract

Sufficient freshwater is needed for water dependent sectors such as agriculture, nature, drinking water, and industry. However, even in low-lying, flood prone countries like the Netherlands, climate change, weather extremes, economic growth, urbanization, land subsidence and increased food production will make it more complex to guarantee sufficient freshwater for all sectors. Furthermore, the frequency and amplitude of extremely dry and wet weather conditions is expected to increase. The current Dutch water management system is not designed to anticipate these extremes. Over the last decades, drained Dutch agricultural fields, land consolidation and urbanization resulted in declining groundwater tables. Additionally, the freshwater demand of different sectors (agriculture, industry, drinking water) increased, causing an increased pressure on the regional groundwater system. As a consequence, the annual groundwater table in sandy soil areas dropped over time with the effect that, nowadays, fresh water is becoming scarce in dry periods. In this chapter we provide insight in the shifting water management strategy in the Netherlands (1950-2020), with the corresponding drainage systems, developing from conventional drainage (approx. 1950 - 1990), to controlled drainage (1990's onwards), climate adaptive drainage (2010 onwards) and subirrigation systems (2018 onwards). Furthermore, we provide insight in the effect of subirrigation on groundwater levels and crop yields, based on both international literature and measurements of Dutch field pilots. Although subirrigation can contribute to improved soil moisture conditions for crop growth on field scale, we show that the water volume needed for subirrigation can be large and could put a significant pressure on the available regional water sources. Therefore, efficient and responsible use of the available external water sources for subirrigation (e.g. surface water, treated waste water, or groundwater) is required. Finally, the implementation of controlled drainage with subirrigation asks for correct implementation in the regional balance: it requires an integral, catchment-wide approach.

Keywords

Drainage, (sub) irrigation, drought mitigation, water retention, water logging, drainage water management

2.1 Introduction

The Netherlands is a low-lying, flood prone country, located in a delta in Western Europe (50º - 54º N and 3º - 7º E) (Figure 2.1-I). Sufficient freshwater is needed for the water dependent sectors as agriculture, nature, drinking water, and industry. These sectors account for 193 billion euros, ± 16% of the Dutch economy (Ministerie van V&W and Ministerie van EZ, 2016). However, climate change, weather extremes, economic growth, urbanization, land subsidence and increased food production, among other things, will make it more complex to guarantee sufficient freshwater for all sectors.

Due to climate change, the range of weather extremes from extremely dry to extremely wet is expected to increase and to occur more frequently (Klein Tank et al., 2014; Philip et al., 2020; Van Oldenborgh et al., 2009). The Dutch sandy Pleistocene uplands (Figure 2.1-I) are particularly drought sensitive as these are rain fed and water supply from rivers is limited (National Deltaprogram, 2014). However, June 2016 was extremely wet in parts of the Pleistocene uplands, with flooding as a result. The years 2018, 2019 and 2020 were extremely dry in these regions (Van den Eertwegh et al., 2021) (Figure 2.1-II). However, the water management system is not designed to anticipate both weather extremes. The challenge is therefore to design a resilient soil-water system to be able to anticipate both (extremely) wet and dry periods.

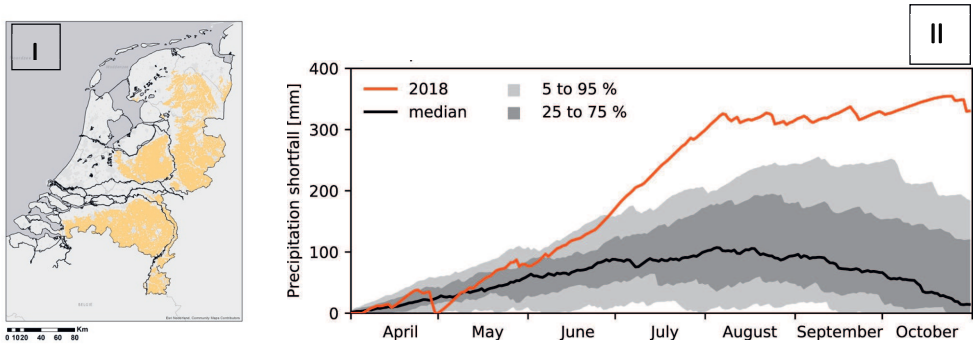


Figure 2.1: I: The Netherlands with the (drought sensitive) sandy Pleistocene uplands (yellow) (± 0 – 100 m+MSL). II: The climate in the Netherlands is typically oceanic, meaning: fresh summers and cool winters. Precipitation is 850 mm per year on average, the reference evapotranspiration (according to Makkink (1957)) is ± 559 mm per year on average (Klein Tank et al., 2014).The cumulative rainfall deficit (precipitation minus reference evapotranspiration in the growing season) ranges between 100 mm for average years (black line, based on years 1981-2010, Weather Station De Bilt) and more than 300 mm for dry years such as 2018 (Van den Eertwegh et al., 2021) (red line). Figure adapted from Philip et al. (2020).

In the Netherlands, most agricultural fields have been drained to quickly get rid of excess water (Ritzema and Stuyt, 2015). Lower groundwater tables and an increase in crop production were the results. Over the past decades, however, excessive drainage contributed to desiccation. Additionally, groundwater is used for drinking water production and industrial applications, resulting in declining groundwater tables. These activities affect nature areas by drought stress, less upward seepage water, and brooks and fens that

become dry (Hoogland et al., 2010). The combination of the increasing food production, a reduction of the available amount of fresh water, and an increase in the freshwater demand, will lead to more freshwater scarcity and necessity for more efficient use of freshwater resources (Witte et al., 2019). These future challenges ask for a good understanding of historic developments and future needs in the use of drainage systems within the regional water management.

Subsurface drainage is essential to make the areas suitable for agriculture, because of the otherwise too shallow groundwater table. From ± 1000 A.D. onwards several drainage systems have been applied in the Netherlands (Haartsen et al., 2010; Hoeksema, 2007; Hooghoudt, 1952; Ritzema and Stuyt, 2015; Ritzema and van Loon-Steensma, 2018; Van Baars, 2005). After the Second World War, the Dutch population grew and more food production was needed. Agricultural fields were intensively drained to lower the groundwater table (Figure 2.2). Furthermore, land consolidation (Van den Noort, 1987; Vitikainen, 2004) and urbanization impacted the water levels (Witte et al., 2019) (Figure 2.2). Nowadays, drainage systems still quickly discharge fresh water out of regions. Additionally, the water demand for irrigation (agriculture), drinking water production and industry increased, resulting in increased groundwater abstractions. As a consequence of this intensified drainage, urbanization and increased groundwater abstractions, the yearly average groundwater table in the sandy Pleistocene uplands (Figure 2.1-I) dropped by ± 33 cm over the last century (Knotters and Jansen, 2005). This desiccation (Figure 2.2) negatively affects biodiversity (Hoogland et al., 2010; Witte et al., 2019).

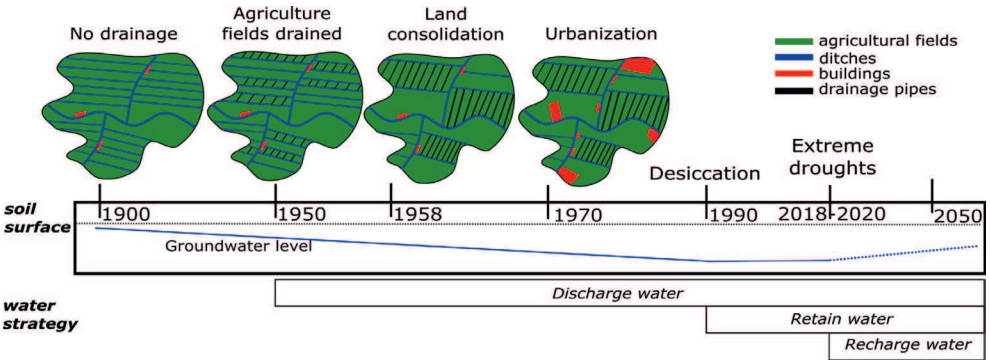


Figure 2.2: Timeline with developments which impacted the landscape design and the groundwater levels in the Netherlands. Desiccation started already around 1950; the main water management strategy was to discharge water. From 1990 onwards the agricultural management anticipated on preventing drought stress through i) discharge water to avoid flooding or waterlogging, and ii) retain water when possible. From 2018 onwards the agricultural management changed more to i) discharge water to avoid flooding or waterlogging, ii) retain water in the soil during rainfall, and iii) recharge water to prevent agricultural and hydrological drought. The scheme applies to groundwater-dependent systems (i.e. <3 m-ss).

Besides measures to anticipate flooding and waterlogging, measures for water retention are needed to be able to anticipate weather extremes, to lower the anthropogenic pressure on the groundwater system, and to guarantee the water availability for different sectors in dry periods. Drainage systems can contribute to this. Besides discharging water, they have the potential to retain and recharge water in the soil-water system as well. In the

latter case, drainage systems are used for subirrigation. These systems are typically relevant for areas with relatively shallow (1 - 3 m-ss) phreatic groundwater levels, like the Dutch sandy Pleistocene uplands, because of the highest urgency regarding declining groundwater levels and increased irrigation water demand.

The objective of this article is to provide insight into the development of drainage systems including the corresponding drainage strategies and the consequences for the groundwater and surface water system (Figure 2.2). This article includes the functionality of different drainage systems in agriculture, and the effect of drainage/subirrigation systems on the groundwater table and water balance components, based on both international literature and field experiments in the Dutch sandy Pleistocene uplands. We describe drainage/subirrigation systems applied in the Netherlands over the last decades, including their effect on the field water balance. Additionally, we discuss the challenges for future implementation of drainage/subirrigation systems in the (regional) water system, balancing between discharge, retention and recharge.

2.2 Drainage systems

2.2.1 Strategy drainage systems in the Netherlands

From the Second World War onwards the Dutch strategy was to increase drainage capacity and quickly discharge water surplus (Figure 2.2). Later on, drainage systems were adapted to also be able to conserve water during periods when drainage was not needed. The water management approach shifted in 2008 to a three-step approach with decreasing priority: 1) retain excess of water in the field, 2) store water in the (regional) drainage system, and finally 3) discharge water to the river (Deltacommission, 2008; Ritzema and Stuyt, 2015). This approach anticipates hydrological events: a decrease in peak discharges during heavy rainfall to prevent flooding and an increase in water storage for use in dry periods (Ritzema and van Loon-Steensma, 2018). Such adaptive water management is necessary to create enough storage capacity before heavy rainfall occurs. The different water strategies resulted in an evolution of drainage systems over the last decades (Table 2.1), as further described in the next paragraph.

2.2.2 Subsurface drainage systems in the Netherlands

No drainage

The term drainage is internationally used to describe that the groundwater table is lowered through measures as ditches and drainage pipes (Stuyt, 2013). Here, we focus on fields with subsurface pipe drainage (Stuyt, 2013). The period with no drainage is mainly the period before the Second World War. Agricultural fields were surrounded by ditches, but pipe drainage was not common, resulting in bulging groundwater tables between the ditches (Figure 2.3-I). Yield losses occurred in wet years due to waterlogging.

Table 2.1: Subsurface drainage systems in the Netherlands (1950-2020) related to the corresponding water management strategy, method to control the drainage level, authority to control the system and scale to which the strategy applies.

Drainage system	Drainage strategy	Drainage level controlled via	System controlled by	Water system scale
No drainage	-	-	-	-
Conventional drainage	Discharge water	-	-	
Controlled drainage	Discharge water Retain water	Ditch	Water Board and/or farmer	Regional water system
Composite controlled drainage	Discharge water Retain water	Control pit	Farmer	Field water system
Composite controlled drainage with subirrigation	Discharge water Retain water Recharge water	Control pit	Farmer	Field water system

Conventional drainage

Conventional drainage consists of single drainage pipes discharging on a ditch (Figure 2.3-II). The drainage pipes are installed higher than the maintained ditch level; drainage stops if the groundwater level is below the height of the drainage system (Stuyt, 2013). Conventional drainage was installed on a large scale after the Second World War (Stuyt, 2013). The primary purpose of conventional drainage is to reduce high groundwater tables in winter and early spring for tillage purposes and to prevent water logging during the growing season (Ritzema et al., 2008; Ritzema et al., 2006). Lowering the groundwater table results in a flatter groundwater table. However, conventional drainage may also introduce drought stress in the summer period, as less water is available (Tan et al., 2002). Nowadays, about 34% of the Dutch agricultural land contains pipe drainage (Massop and Schuiling, 2016).

Controlled drainage

Controlled drainage (or: level-controlled drainage, (Stuyt, 2013)) consists of single drainage pipes connected to the ditch, comparable with conventional drainage, but with drainage pipes below the maintained ditch level (Figure 2.3-III). Doing so, conventional drainage is modified to control the drainage outflow through controlling the water level in a ditch by a weir. The purpose of controlled drainage is to i) prevent unnecessary drainage and conserve water in the regional water system during rainfall, and ii) reduce peak outflows during discharge. The ditch level is often controlled for a region by water management authorities. This means that effects of controlled drainage can be different for upstream and downstream parcels.

Composite controlled drainage

Composite controlled drainage contains a drainage system where the single drains are connected by one collector pipe at the end of the field (Figure 2.3-IV-1). The collector pipe is connected with the control pit and the control pit is connected with the adjacent ditch.

The difference between controlled drainage and composite controlled drainage is that the drainage level by composite controlled drainage is regulated by the control pit via the farmer for one agricultural field, instead of by a water management authority for a larger region. The control pit contains a fixed weir structure. The water level in the control pit is equal to the water pressure in the drainage pipes. The system allows to retain water within agricultural parcels and to maintain specific groundwater levels, controlled by the farmer:

1. Discharge water to lower the groundwater level during wet periods. Drainage outflows can be reduced and controlled. Drainage occurs if the weir crest in the control pit < the water level in the control pit.
2. Retain and store water in the soil-water system to prevent fast decline of the groundwater level during dry periods and raise the groundwater level during periods of rainfall. Water retention occurs if the weir crest in the control pit > the water level in the control pit.

The dual-purpose of this system fluctuates several times during a crop season, with a focus on water management at field scale. The timing of these functions depends on the geographical characteristics of the area as local rainfall patterns, regional surface water management (winter and summer water levels maintained by water authorities), water supply area or free drainage area, soil type, and regional groundwater flow. Composite controlled drainage works effectively in areas that are nearly flat (surface slope < 1%) (Ayars et al., 2006; Carstensen et al., 2020; Massey et al., 1983). In-field differences in the groundwater table are automatically levelled.

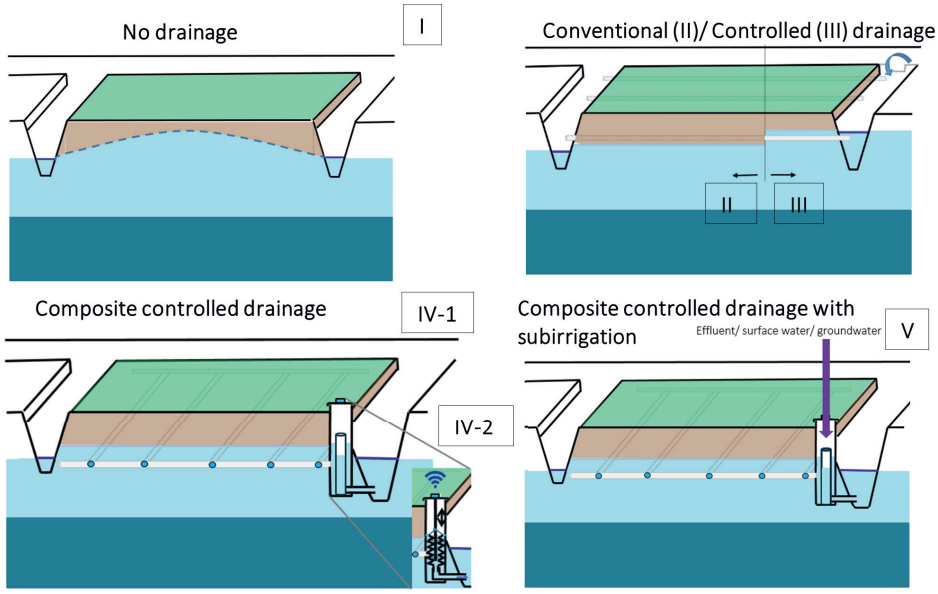


Figure 2.3: Agricultural field without pipe drainage (I), with conventional drainage (II), with controlled drainage (III), with composite controlled drainage with a fixed weir (IV-1) or an online controlled weir structure (IV-2) and composite controlled drainage with subirrigation controlled by a fixed weir or online controlled weir structure (V).

Climate adaptive drainage

Climate adaptive drainage (CAD) is a technological advanced example of composite controlled drainage, where the weir structure in the control pit can be automatically online controlled (Van den Eertwegh et al., 2013) (Figure 2.3-IV-2). An important difference between a 'basic' composite controlled drainage and CAD is the process of managing the drainage level in the control pit. For CAD the drainage level can be controlled remotely through the internet and any drainage level (between a physical maximum and minimum) can be set. For 'basic' composite controlled drainage the drainage level can only be controlled manually and only few drainage levels can normally be set. By combining the CAD-system with a CAD-management algorithm, the required drainage level can be set automatically based on weather forecasts and the current hydrological status of the field, thus actively controlling the soil moisture conditions in the root zone (Bartholomeus et al., 2015b).

The CAD-management algorithm (Bartholomeus et al., 2015b) combines field measurements (precipitation, groundwater table, soil moisture content, crest level, and ditch level), the actual weather forecast, and the numerical hydrological SWAP model for the unsaturated zone (Kroes et al., 2017) combined with the optimization algorithm PEST (Doherty, 2010) to estimate the optimal crest level. The algorithm takes into account preventing oxygen stress (according to Bartholomeus et al. (2008)), and preventing unnecessary discharge.

Composite controlled drainage with subirrigation

The current (composite) controlled drainage systems can be modified to systems for controlled drainage with subirrigation (Figure 2.3-V), by supplying (external) water into the control pit. This water could flow into the control pit directly or through active pumping. The water pressure in the drainage systems raises as consequence of subirrigation. If the water pressure in the drainage system is higher than the groundwater level, water infiltrates from the drainage pipes into the soil. The goal of subirrigation is to raise the groundwater level (Figure 2.4) and to increase the soil moisture content in the root zone. Thus, controlled drainage with subirrigation could serve three purposes:

1. discharge water,
2. retain water,
3. recharge water.

An external source of water should be available for subirrigation. This can be surface water, water from ponds, recycled drainage water, groundwater or treated (industrial or domestic) waste water (Allred et al., 2003; Ayars et al., 2006; Bartholomeus et al., 2018a; Bartholomeus et al., 2017; Bartholomeus et al., 2018b; De Wit et al., 2021a; Drury et al., 1996; Hay et al., 2021; Narain-Ford et al., 2020; Narain-Ford et al., 2021; Ng et al., 2002; Smith et al., 1985; Tan et al., 2002). Composite controlled drainage with subirrigation is applied in various field experiments in the Dutch sandy Pleistocene uplands (Bartholomeus et al., 2018a; Bartholomeus et al., 2017; Bartholomeus et al., 2016; Bartholomeus et al., 2018b; De Wit et al., 2021b).

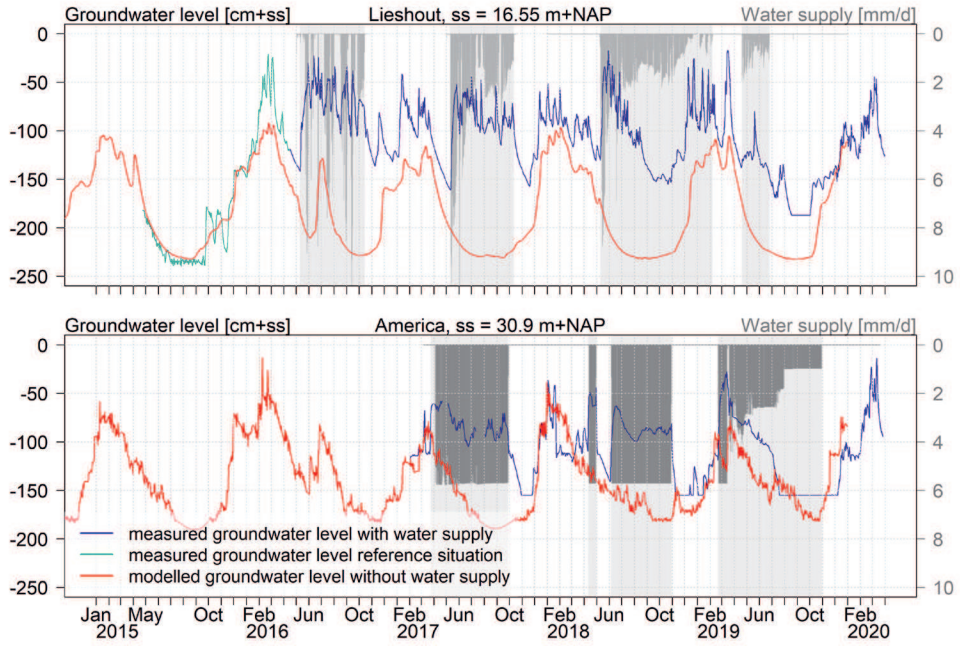


Figure 2.4: Groundwater levels (cm+ soil surface, cm+ss) in two field experiments with a subirrigation-system: with water supply/subirrigation (blue, measured), reference situation (green, measured), and without water supply (red, modelled). The grey blocks represent the period of water supply (subirrigation), the dark grey blocks represent the amount of water supply. Figure adapted from De Wit et al. (2021a).

Figure 2.4 shows the measured and modelled groundwater table of two Dutch field experiments Lieshout and America (De Wit et al., 2021a). The groundwater table raises directly once water is pumped into the drainage system (grey blocks in Figure 2.4). As a result, the groundwater table fluctuates ± 70 / 80 cm below soil surface at the start of the crop season (Figure 2.4). The groundwater table is ± 100 cm higher with external water supply than without water supply in the mid crop season (Figure 2.4). However, Figure 2.4 also shows that the water supply is not enough to maintain the groundwater level in extremely dry seasons (2018 and 2019). The average water supply was ± 400 mm/year in Lieshout (using treated industrial waste water) and ± 900 mm/year in America (using groundwater) in the growing season (± 160-190 days) (De Wit et al., 2021a). That is a high amount compared to the average yearly precipitation surplus in the Netherlands of about 250mm/y (Figure 2.1-II). Additionally, the amount is considerably higher than the average precipitation deficit in the summer period of about 50-100mm/y (Philip et al., 2020). So, although subirrigation could alleviate drought stress at agricultural fields, it could also provide a significant pressure on available water sources. Therefore, it is important to recognize that the use of a specific water supply source for subirrigation will propagate through the regional water system and will affect different components of the regional water balance. Subirrigation using surface water for example can be critical in areas without supplemental water, as ditches can become dry in drought periods. Additionally, especially when using treated wastewater or surface water as supply source, water quality

issues are important (Beard et al., 2019; Dingemans et al., 2018; Narain-Ford et al., 2020; Narain-Ford et al., 2021). All in all, responsible use of available water resources for subirrigation is a key issue.

2.3 Effects of drainage systems on the water balance

Drainage systems directly affect the (ground) water system and all components of the water balance at field scale (Figure 2.5).

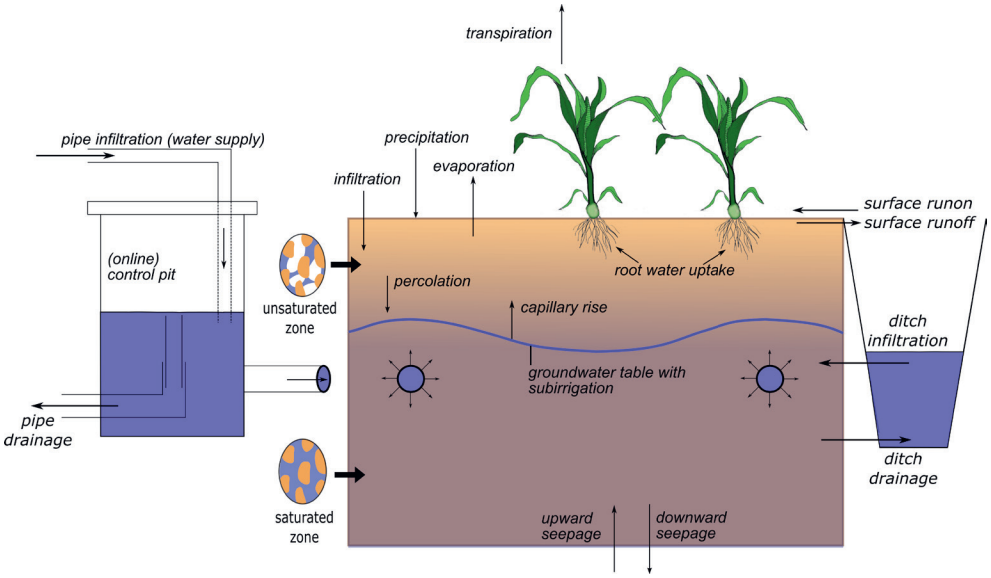


Figure 2.5: The soil water column at field scale with the water balance components in the (un)saturated zone.

Besides in countries like the Netherlands, drainage systems are commonly applied in the USA (Doty and Parsons, 1979; Skaggs et al., 2012a), in arid regions with irrigated agriculture like Egypt and Pakistan (Abdel-Dayem and Ritzema, 1990; Ritzema, 2007), in Australia (Christen et al., 2001), and in India (Ritzema et al., 2008). Table 2.2 and Table 2.3 provide an overview of field experiments on conventional drainage vs. controlled drainage and controlled drainage vs. subirrigation respectively, providing quantitative information on the effect of the different drainage systems on water retention and water supply.

Table 2.2: Literature overview focused on i) effects of (composite) controlled drainage compared to conventional drainage for groundwater table, relative increase of crop yield, crop type, and ii) system design characteristics: drain spacing and drain depth. The values in the table are copied from the reference paper.

Reference	Country	Soil	Groundwater table (m-ss)		Crop		Drain characteristic	
			Conventional drainage	Controlled drainage	Yield (%)	Type (-)	Spacing (m)	Depth (m)
Abdel-Dayem and Ritzema (1990)	Egypt	Clay	-		+10 +130	Rice Wheat	15 to 60	1.2 to 1.7
Grigg et al. (2004)	USA	Silt loam	-	-	-3	Corn	15	1.25
Wesström and Messing (2007)	Sweden	Loamy sand	0.80	0.20 to 0.60	+ 2 - 18	Grain	10	1.0
Delbecq et al. (2012)	USA	Silty (clay) loams	-	-	+ 5.8 - 9.8	-	-	-

Table 2.3: Literature overview focused on i) effects of composite controlled drainage with subirrigation ('sub') compared to systems without subirrigation ('no sub') for groundwater table, relative increase of crop yield ('yield'), crop type ('type'), and water supply amount ('amount') and water supply period ('period'), ii) system design characteristics: used water source, drain spacing and drain depth. The values in the table are copied from the reference paper.

Reference	Country	Soil	Groundwater table		Crop		Water supply		Water source	Drain characteristic	
			No sub (m-ss)	Sub (m-ss)	Yield (%)	Type (-)	Amount (mm)	Period (d)		Spacing (m)	Depth (m)
Hooghoudt (1952)	NL	Heavy clay	1.0	0.40/ 0.45	+ 84	Hay	4 mm/d	100	Surface water	2.0	0.6/ 0.8
Massey et al. (1983)[1]	Site 1 /USA	Loamy sand	-		-		227[1]		-	40	1.0
	Site 2 /USA	Loamy sand	-		-		171[1]		-	30	1.0
	Site 3 /USA	Loamy sand	-		-		296[1]		-	15	1.0
Doty and Parsons (1979)	USA	Sandy loam		0.6 higher	[2]		410 (1975), 260 (1976)	135	-	32	1.2
Smith et al. (1985)	USA	Sandy loam	1.0[3]	0.70	-		305.1	135	Surface water	15	1.0
Drury et al. (1996)	Canada	Clay loam	1991: 1.22, 1992: 0.92, 1993: 1.30, 1994: 1.10	1991: 0.95, 1992: 0.55, 1993: 0.60, 1994: 0.50	-		109 (1991, 1993, 1994) 5.7 (1992)[4]	± 76	Irrigation pond	7.5	0.6
Fisher et al. (1999)	USA	Silt loam	-		7 (1995) 45 (1996)	Corn	-		-	5	0.75
Mejia et al. (2000)	Canada (1995)	Silt loam	1.30	0.91[5]	+ 13.8		223	-		18.3	1.0
	Canada (1996)		1.21	0.75	+ 6.6		248	-			
Ng et al. (2002) and Tan et al. (1999)	Canada	Sandy loam	1.31	0.82	+ 64	Corn	183.9	60	Surface water (lake)	6.1	0.60
Allred et al. (2003)	USA	Clay	-		Dry years + 34.5 + 38.1	Corn Soybeans	-		Re-use runoff water	2.4 to 4.9	0.76 to 0.91
					Wet years + 14.4 + 9.7	Corn Soybeans					
					Average + 19.6 + 17.4	Corn Soybeans					
Hornbuckle et al. (2005)[6]	Australia	(clay) loam	0.3 higher				143	17	-	36	1.8 to 2.2
Wesström et al. (2014)[6]	Sweden	Sandy loam	0.30 to 0.70		+ 6-10 + 20	Potatoes Wheat	2002: 60 2003: 80	-	-	16	1
Jouni et al. (2018)[7]	Iran	Silty clay	1.11	0.71	+ 27	Wheat	731	± 242	-	80	2.0

[1]: The values are based on the 27-year average results predicted by the model DRAINMOD, validated on 3 field sites. Most important assumptions in the model: water level in the outlet was constant (this reduced the soil storage available for precipitation and increased drainage and surface runoff). The values are per growing season, the exact days of a growing season are not given in the paper.

[2]: Yield increases with increasing pipe drain spacings. No yield was measured at a reference situation.

[3]: It was not a reference situation, but different subirrigation systems were used for differences in groundwater table effects through subirrigation. The average results of control method C are presented.
[4]: The year 1992 is reported. However, almost no subirrigation was added due to a large amount of rainfall in the growing season. The year 1992 is not included in the calculation of water supply to a 'standard' growing season of 180 days.
[5]: The controlled drainage experiment with a drainage level of 0.50 m – ss is used ($CWT_{0.50}$)
[6]: The experimental fields were fields with free drainage (conventional drainage) and controlled drainage, both with subirrigation.
[7]: Only yield of the wheat from the experiments free drainage and controlled drainage 70 cm is shown. Another experiment, and two other crops are also reported in the article.

Controlled drainage vs. conventional drainage

The main difference in strategy between controlled drainage and conventional drainage is retention of water (Figure 2.3, Table 2.2), to reduce discharge and keep the groundwater level and soil moisture availability at a sufficient level for crop growth. This process affects different water balance components:

- Pipe drainage decreases compared to conventional drainage because the ditch water level could be controlled (Bonaiti and Borin, 2010; Drury et al., 1996; Hornbuckle et al., 2005). The decrease of pipe drainage follows partly due to an increased soil water storage capacity through the controlled drainage. Riley et al. (2009) showed a decreased pipe drainage of 14% in a lysimeter experiment. Skaggs et al. (2010) reported in different controlled drainage field experiments in the USA a decrease in pipe drainage of 16 to 29% in clay soils, and 17 to 85% in sandy loam. Jeong et al. (2018) reported a decrease of 51% in silty clay soils. Wesström and Messing (2007) observed a decrease of 5-35% in sandy loam. Rozemeijer et al. (2016) published data for the Netherlands, with drainage values (November-April) in a reference period of 303 mm for conventional drainage compared to 163 mm (2009-2010) and 127 mm (2010-2011) for controlled drainage. Controlled drainage thus leads to an increase in water retention (Table 2), i.e. water that would have been discharged to the surface water when using conventional drainage remains in the groundwater system with controlled drainage (Skaggs et al., 2010).

- Actual evapotranspiration (ET_{act}) increases through improving drainage conditions and improved soil moisture conditions (Abdel-Dayem and Ritzema, 1990), and herewith less drought stress in summertime. This leads to increased crop yields (Table 2.2). The reviewed field studies in Skaggs et al. (2010) showed a maximum ET_{act} increase of 10% for corn with controlled drainage compared to conventional drainage. Evans and Skaggs (1985) reported an increase of 2 to 5% for corn yield in the USA. Doty et al. (1975) found a general rule that the silage yield of corn could increase by 0.5 t/ha for each day that the water table was maintained at less than 100 cm below soil surface in a sandy Coastal Plains soil (USA). However, Grigg et al. (2004) reported a decrease of 3% in corn yield with controlled drainage in the

USA (Table 2.2) because of a too shallow water table for the roots early in the growing season. This shows that proper management of controlled drainage systems is required in order to increase water availability to prevent drought stress, while preventing oxygen stress too (Bartholomeus et al., 2008; Hack-ten Broeke et al., 2016).

- Surface runoff could either increase or decrease, depending on the hydrological boundary conditions, soil physical properties and rain intensities. An increase is modelled by Singh et al. (2007) and Skaggs et al. (2010) and observed in a lysimeter experiment (Riley et al., 2009) and field experiment (Drury et al., 1996; Grigg et al., 2004). Wesström et al. (2014) reported a decrease in runoff through controlled drainage compared to conventional drainage, from 254-319 mm to 151-187 mm per year (1 July – 30 June).

- Downward seepage (groundwater recharge) increases as result of controlled drainage (Singh et al., 2007). However, downward seepage is a difficult water balance term to measure. Skaggs et al. (2010) stated therefore that the downward seepage rate with controlled drainage will be approximately equal to the natural drainage rate that occurred before installing the controlled drainage system. This will be the case if ET_{act} with controlled drainage is equal to ET_{act} of the original situation.

Controlled drainage thus leads to an increase in water retention. This water is available for crops, recharges the groundwater or slowly discharges to the surface water through the subsoil. It should be noted, however, that significant water retention with controlled drainage could only be achieved if shallow drainage levels are maintained already in spring. Furthermore, once water has been discharged in early spring, significant water retention can only be realized as significant rainfall occurs too.

All in all, the development of different drainage systems, affected the water balance terms over time (Table 2.2):

- No drainage: ET_{act} is limited as consequence of too wet conditions. Because of the wet conditions, surface runoff and ditch drainage are high.
- Conventional drainage: Compared to 'no drainage', discharge through pipe drainage increases, groundwater recharge and runoff decrease. ET_{act} increases as result of less oxygen stress and earlier opportunities for tillage. However, excessive drainage and herewith too low groundwater levels in summertime may result in drought stress and reduced ET_{act}.
- Controlled drainage: Compared to 'conventional drainage' pipe drainage decreases and downward seepage increases (Table 2.2). Surface runoff may either increase or decrease. ET_{act} mainly increased, but can decrease with poor water level control (i.e. creating too wet conditions).

Composite controlled drainage with subirrigation vs. (composite) controlled drainage

The main difference in strategy between composite controlled drainage and subirrigation is active recharge of water (Figure 2.3, Table 2.2) to raise the groundwater level and increase soil moisture availability for crops. Water balance components are strongly affected by subirrigation:

- Pipe infiltration increases through subirrigation, which is by definition the main difference between composite controlled drainage and composite controlled drainage with subirrigation: water is actively added to the system. The infiltration amount found in international literature varies between 170 and 410 mm, but the water supply periods differ as well (Table 2.3). When the water supply data from Table 2.3 are transposed to a 'standard' growing season of 180 days, cumulative infiltration ranges between approximately 250 – 1500 mm/180days. Ranges are high, due to differences in required raise of groundwater level, length of the growing season, and water losses through lateral ditch drainage and downward seepage (Smith et al., 1985). The groundwater table is typically raised by approximately 30 to 40 cm (Table 2.3). The main water supply source used for subirrigation is surface water (Table 2.3).

- ET_{act} increases through subirrigation, but it is strongly related to the effects in groundwater table. Due to a shallower groundwater table, an upward flux is expected from the water table through the unsaturated zone to the root zone. However, the rate of upward flux decreases rapidly when the distance between the water table and the rootzone increases (Smith et al., 1985). For example, the upward flux could be 6 mm/d at a water table depth of 70 cm below the rootzone, but decreases to 2 mm/d at water table of 90 cm below the rootzone for a sandy loam soil (Smith et al., 1985). However, this flux strongly varies between soil types (Table 2.2). Increased yields have been found, ranging from +6.6% (Mejia et al., 2000) to +64% for corn in the USA (Ng et al., 2002). Assuming a linear relationship between relative yield and relative transpiration (De Wit, 1958), transpiration will show a similar increase.

- Downward seepage increases through subirrigation (Massey et al., 1983; Smith et al., 1985). Downward seepage values are strongly site dependent, as recharge depends on the soil hydraulic conductivity, the natural water table depth, and the water level in adjacent ditches or canals (Massey et al., 1983; Smith et al., 1985). In general, higher ditch levels result in less lateral drainage to ditches and more downward seepage (Hooghoudt, 1952).

- The exact annual effects of subirrigation on water balance components depend on the required increase in groundwater level, soil properties, site conditions, ditch water level, crop characteristics and drain criteria (Singh et al., 2007; Skaggs et al., 2010; Skaggs et al., 2012a). The maintained drainage and ditch level have been identified as most important factors for the results on the increased groundwater table and water balance components (Hooghoudt, 1952; Jouni et al., 2018; Mejia

et al., 2000). Most advantages with subirrigation are reached in drier summers, rather than in wet summers (Mejia et al., 2000). Given the large amounts of water recharged through subirrigation systems, the order of magnitude of different water balance components will be mostly in the range of hundreds of mm on a yearly basis.

All in all, the development of subirrigation caused differences in water balance terms compared to only composite controlled drainage (Table 2.3):

- Composite controlled drainage: the water balance components are similar to controlled drainage.
- Composite controlled drainage with subirrigation: the modified composite controlled drainage aims to recharge water as well. During periods of drainage (discharge) the water balance components will be similar to composite controlled drainage. In subirrigation periods, the components pipe infiltration, downward seepage / groundwater recharge and ET_{act} increase compared to composite controlled drainage (Table 2.3).

The differences in water balance terms caused by development of drainage systems are summarized in Table 2.4.

Table 2.4: The effects of drainage systems (no drainage, conventional drainage, controlled drainage, composite controlled drainage, composite controlled drainage with subirrigation) on the water balance components are described as o = no effect, - = decrease of this component, + = increase of this component. All effects of a drainage system are compared to the situation with the previous drainage system. Effects based on literature overview in Table 2.2 and Table 2.3.

Drainage system	Surface runoff	Ditch infiltration	Ditch drainage	Pipe infiltration	Pipe drainage	Downward seepage*	ET_{act} *	
							wet	dry
No drainage								
Conventional drainage	-	o	-	o	+	-	+	-
Controlled drainage	+	-	o	+	-	+	- / o	+
Composite controlled drainage	o	o	o	o	o	o	o	o
Composite controlled drainage with subirrigation	o	-	o	+	o	+	o / -	+

* actual evapotranspiration (ET_{act}) can increase (+) or decrease (-) as result of either too wet ('wet') or too dry ('dry') conditions.

2.4 Local and regional implementation of controlled drainage with subirrigation

Changes in drainage systems were mainly triggered by land use changes as consequence of social and economic changes as clearly showed in literature, resulting in declining groundwater tables (Figure 2.6). Although the water management is now in a process towards a more adaptive approach (Van der Brugge et al., 2005), a resilient soil water system is needed to anticipate the expected (future) weather extremes (Figure 2.2). Table 2.2 and Table 2.3 show that controlled drainage systems can contribute to water retention when compared to conventional drainage systems, but also that subirrigation could be applied to actively recharge the groundwater. Doing so, crop water availability could be managed in a more adaptive manner. However, literature also shows that only part of the water used for subirrigation is used for root water uptake, and part of the applied water feeds the groundwater system (increased downward seepage). Furthermore, the total amount of water used for subirrigation can be large, which could put a significant claim on the available water sources. Therefore, subirrigation systems should be implemented in such a way that they fit within the regional management.

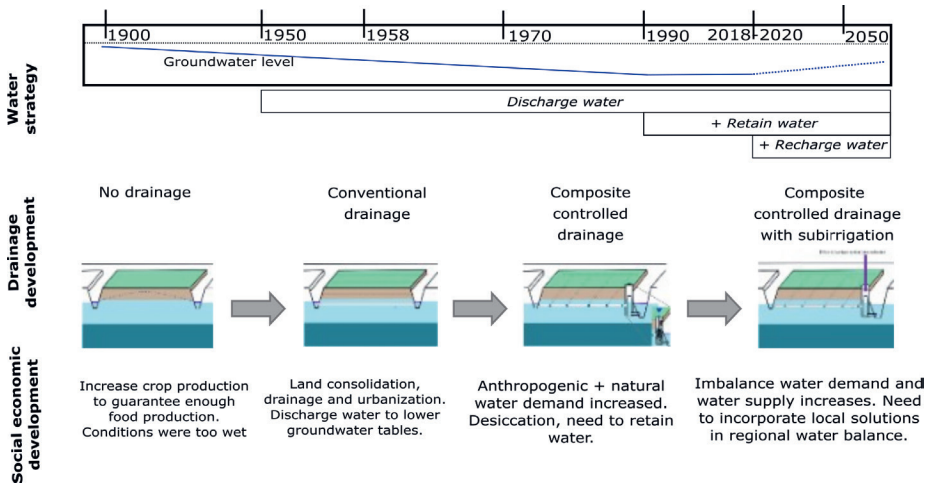


Figure 2.6: Drainage development in the Netherlands occurred parallel to social and economic changes in the last decades.

Local and regional scale components affect the desired effects of controlled drainage systems with subirrigation (Figure 2.7). Requirements for such a system on local (field) scale are the technical design of the drainage system in relation to environmental characteristics. Local characteristics directly affect the water table and thus the growing conditions of crops. Depth and spacing of drain pipes varies throughout the reported field experiments (Table 2.2, Table 2.3). Drain spacing is often a function of drainage criteria (Ayars et al., 2006; Ritzema et al., 2008; Skaggs et al., 2012a). Two reasons for a narrower drain spacing are a faster water removal in drainage mode, and a more uniform water distribution in the soil in subirrigation mode (Allred et al., 2003). The required pump capacity depends on the required water supply (frequency and capacity) and the determined drainage level. More

efficient water use can be obtained through non-continuous pumping or to store and infiltrate drainage water in the winter period for the growing season (Massey et al., 1983). The intended drainage level can be constant e.g. 0,7 m-ss, or can be varied according to the crop stage and thus root development (Jeong et al., 2018), or the groundwater table (Giardini et al., 1995). Proper management is necessary to avoid too shallow water tables in the early growing season, that negatively impacts the root proliferation or might result in oxygen stress, and thereby limit crop growth (Grigg et al., 2004). The pumping strategy could be optimized to reach the intended drainage level, while minimizing the water supply (Smith et al., 1985). Soil characteristics are not changeable, but effects of controlled drainage with subirrigation differ with soil characteristics (Doty and Parsons, 1979). Fox et al. (1956) and Yu et al. (2020) reported that a soil layer with limited permeability at a shallow depth is needed with subirrigation to avoid extreme downward seepage losses. Finally, ditch levels surrounded by the field are important as a shallow groundwater table with low ditch levels results in lateral drainage, an unfavorable effect (Giardini et al., 1995). Adjusting surface water levels in adjacent canals/streams is recommended to minimize lateral drainage of infiltrated water. The implementation of a controlled drainage system with subirrigation should thus include the soil, crop, hydrological and meteorological characteristics of a site (Ayars and Evans, 2015; Skaggs, 1981; Skaggs, 1987).

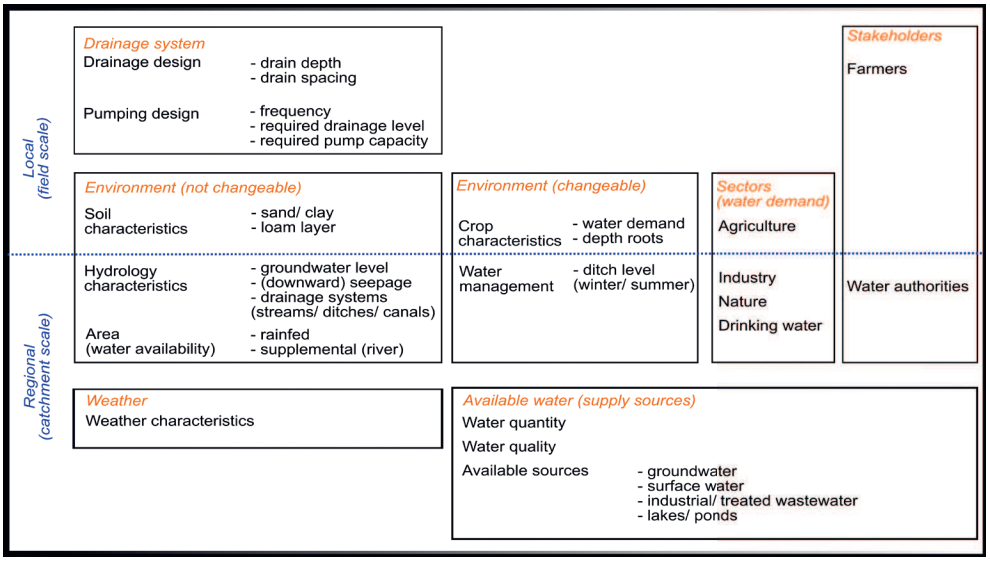


Figure 2.7: Overview of local and regional scale components to take into account when implementing controlled drainage with subirrigation systems.

Applied sources of water supply are collected rain water (Drury et al., 1996), surface water (Tan et al., 1999), and collected drain water (Allred et al., 2003). Besides these relatively common water sources, use of alternative water sources, like treated wastewater, is being explored (Narain-Ford et al., 2021). First of all, the water source must be of a sufficient quality to use it for subirrigation. However, given the significant changes of water balance components due to subirrigation (see previous section) also in terms of water quantity the

propagation of the water use for subirrigation throughout the whole water system should be quantified. Hardly any literature is available about the application of different water sources for subirrigation and the impact of the used water source on the regional water system. However, in many countries, there are competing claims on water sources; the water demand not only comes from the agriculture sector, but also from the industry, drinking water, and nature (Zikos and Hagedorn, 2017). When subirrigation is applied on regional scale, the implementation requires knowledge of the entire regional water cycle, including the anthropogenic water demand of different sectors that are already putting claims on the same water sources (Figure 2.8) (Pronk et al., 2021). Besides that, efficient use of water sources is required to sustain the regional groundwater table (Xue et al., 2017). In this context, controlled drainage with subirrigation is a special method as water is used for increased evapotranspiration and crop yields, while limiting (ground)water abstractions for sprinkler irrigation, but also to replenish groundwater (Table 2.4). Doing so, subirrigation has the potential to keep water within the regional groundwater system, that would have been discharged otherwise.

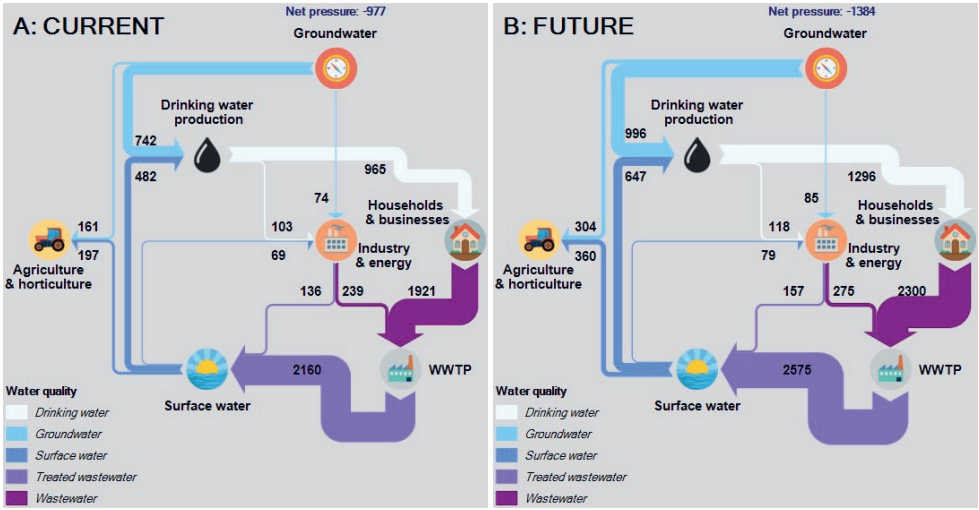


Figure 2.8: Composite controlled drainage with subirrigation at field scale (part of 'Agriculture and horticulture') needs to fit in the regional water availability and demand for that water by multiple sectors. Exploitation of water resources for subirrigation purposes will propagate through the whole water system. Left figure represents the anthropogenic water system of the Netherlands for the current situation, the right represents the anthropogenic water system of the Netherlands for the future (2050) situation. The flows and the net pressure on the groundwater system are given in million m^3 $year^{-1}$. Details about the flows are described in Pronk et al. (2021). Figures adapted from Pronk et al. (2021).

In order to incorporate subirrigation within the regional water balance, insights in the regional water availability and the propagation of water use for subirrigation throughout the whole water system needs to be quantified. Given the large ranges in water needs found in literature, it is clear that regional scale water needs for subirrigation systems should be known, before they could be incorporated in the regional water management in a responsible manner.

Controlled drainage with subirrigation has been described in literature over the past decades, focusing on effects on local scale (Table 2.3). It is important to apply this field scale knowledge in the current changing water strategy of water retention and water recharge on regional scale (Figure 2.2). Correct implementation of controlled drainage with subirrigation in the regional water system is an integral, catchment-wide question with different challenges (Figure 2.7):

- Insight is necessary in the water availability for subirrigation of each location, both in space and time.
- Efficient water supply and minimizing the water supply could be reached through optimized pumping strategy (Smith et al., 1985).
- Water resources, other than surface water, could be used for water supply, like industrial or treated wastewater. Important conditions are sufficient water quality and limited negative side effects during the propagation through the entire water system (Pronk et al., 2021).

2.5 Conclusion

This chapter gives insight in the development of drainage systems over time in the Netherlands, occurring parallel to the structurally declining groundwater levels. Literature showed clearly that changes in drainage systems were mainly triggered by land use changes as consequence of social and economic changes (Figure 2.6). However, the main Dutch water management system is still focused on discharging water (Ritzema and Stuyt, 2015; Ritzema and van Loon-Steensma, 2018). To cope with the imbalance in water demand and water supply and climate change, controlled drainage with subirrigation could be a viable measure to i) discharge, ii) retain and iii) recharge water. This system has the potential to 1) improve growing conditions for crops at field scale, 2) reduce peak discharges at regional scale, and 3) discharge less water at regional scale and increase groundwater recharge.

Drainage systems affect most water balance components (Table 2.4). Controlled drainage increases especially ET_{act}, downward seepage and runoff, while pipe drainage decreases. The biggest advantage of controlled drainage with subirrigation is to supply water, raise the groundwater level and improve the soil moisture conditions for crop growth, while still having the option to discharge water when needed. Another advantage of controlled drainage with subirrigation compared to controlled drainage is that it could contribute to increased water retention and recharge (Table 2.4). However, it could significantly alter water balance components. Therefore, correct and responsible implementation of subirrigation in the regional system is needed (Figure 2.7), which requires knowledge on the effects of controlled drainage with subirrigation throughout the entire water system.



CHAPTER 3

HYDROLOGICAL CONSEQUENCES OF CONTROLLED DRAINAGE WITH SUBIRRIGATION

"YOU CANNOT STEP INTO THE SAME RIVER TWICE" - HERACLITUS

This chapter is based on the publication:
De Wit J.A., Van Huijgevoort M.H.J., Van Dam J.C., Van den Eertwegh G.A.P.H., Van Deijl D., Ritsema C.J., Bartholomeus R.P. (2024) Hydrological consequences of controlled drainage with subirrigation. Journal of Hydrology 628:130432. DOI: https://doi.org/10.1016/j.jhydrol.2023.130432.

Data availability
Field measurements used in this chapter are available via https://doi.org/10.4121/6e5f65f6-530f-438d-8e43-3593e259aaba

Supplementary material
Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2023.130432

Highlights

- Water supply and pit level are simulated dynamically to understand subirrigation.
- Geohydrological settings determine the hydrological propagation of subirrigation.
- Subtle differences in geohydrology define if subirrigation improves crop yield.

Abstract

Controlled drainage with subirrigation (CDSI) could be a viable measure to cope with the imbalance in water demand and supply in groundwater dependent regions. CDSI has the potential to i) retain, ii) recharge and iii) discharge groundwater, i.e. anticipate both dry and wet weather extremes. The aim of this chapter is to specify the hydrological consequences of CDSI at field scale. Four field CDSI pilots with varying geohydrological conditions in Dutch sandy Pleistocene uplands were monitored (minimum 5 years) to study the effects on groundwater level, soil moisture content and soil water potential. Dynamic modelling using the SWAP-model, calibrated with PEST, was used to quantify all water balance components for the field pilots, needed for responsible implementation of CDSI. Using SWAP-PEST, measured groundwater levels and soil moisture conditions were reproduced sufficiently accurate. Both the water supply rates and the water and crest levels in the control pit of CDSI systems could be simulated dynamically, which is an important improvement to earlier modelling approaches. Model calculations were used to study the hydrological responses of CDSI for meteorological dry to wet years and for each of the field sites. Simulations show that transpiration increases with 38 to 206 mm in dry years for sites with respectively low and higher hydraulic resistances in the subsoil. Simulations also show that the required water volume can be large (664 – 728 mm, respectively). CDSI could thus improve hydrological conditions for crop growth, but the success depends on subtle differences in geohydrologic characteristics.

Keywords

Controlled drainage, subsurface drainage, subirrigation, SWAP, modelling, field experiments

3.1 Introduction

Sufficient fresh water is needed for water dependent sectors such as agriculture, nature, drinking water, and industry. However, climate change, weather extremes, economic growth, urbanization, land subsidence and increased food production, among other things, will make it more complex to guarantee sufficient fresh water for all sectors. The range of weather extremes from extremely dry to extremely wet is expected to increase and weather extremes are expected to occur more frequently (Philip et al., 2020; Teuling, 2018). However, in many areas the water system is not designed to anticipate both weather extremes, and to cope with the imbalance in water demand and water supply. Controlled drainage with subirrigation (CDSI) systems could be a viable measure to i) retain, ii) recharge, and iii) discharge water. This system has the potential to 1) improve growing conditions for crops at field scale, 2) reduce peak discharges at regional scale, and 3) increase groundwater recharge on regional scale. The aim of this chapter is to specify the hydrological consequences (groundwater level, (*GWL*, i.e. water table in unconfined aquifer), soil moisture content (*SMC*) and water balance components) of CDSI systems at field scale (Figure 3.1).

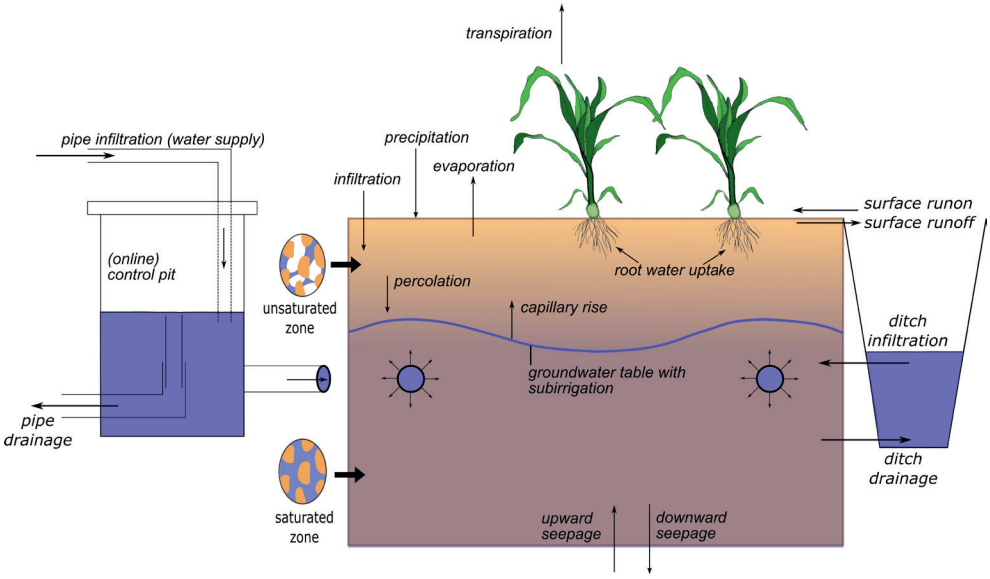


Figure 3.1: The soil water column at field scale with the water balance components in the (un)saturated zone. Figure adapted from De Wit et al. (2022).

Drainage systems have been widely installed to remove water in wet periods. About 34% of the Dutch agricultural land, for example, contains pipe drainage (Massop and Schuiling, 2016). Later, some of these systems were converted to controlled drainage to also retain water by reducing drainage (Ayars et al., 2006; Skaggs et al., 2012a). Nowadays, these controlled drainage systems can also be used to pump water into the system and recharge

groundwater, called ‘subirrigation’ (hereafter controlled drainage with subirrigation CDSI) (De Wit et al., 2022; Singh et al., 2022). An external water source of a sufficient water quality has to be available for subirrigation. Different CDSI applications have been described (e.g. Ayars et al. (2006), Bartholomeus et al. (2018b), Hay et al. (2021), Narain-Ford et al. (2021)). CDSI systems can be controlled manually or online (climate adaptive drainage (CAD), Van den Eertwegh et al. (2013)). A key component in the functioning of CDSI systems is the created water level in the control pit as it either forms the drainage base (‘discharge’, ‘retention’) or provides the pressure for infiltration (‘recharge’) (Evans and Skaggs, 1985; Tang, 2022).

The implementation of CDSI systems could alter several water balance components (Figure 3.1). The groundwater level could raise (Drury et al., 1996), and depending on both soil physical conditions determining capillary rise, and crop rooting depth, it could increase crop water availability and crop yield (Ng et al., 2002). However, not all water balance components can be measured. Models as DRAINMOD (Skaggs et al., 2012b), Hydrus (Šejna et al., 2022) and SUTRA (Voss and Provost, 2010) have been applied to design and model CDSI systems. Although models implementing CDSI systems have been described in literature over the past decades, the water level in the control pit (fixed head) or water supply rate (fixed flow) have been considered constants. However, they depend on the drainage threshold in the pit, groundwater level, maximum available external water supply, drainage resistance and infiltration resistance. Therefore, dynamic modelling is required for correct insights in the water balance components and effective implementation of subirrigation (Doty et al., 1986; Evans, 2008). This results in the following research question to be addressed in this study: What are the hydrological consequences of subirrigation and how can these consequences be simulated using a field scale agro-hydrological model?

To answer this research question, we use both field data and dynamic model simulations. We describe the obtained measurements of field pilots with CDSI systems of four experimental sites in the Netherlands, varying in geohydrological characteristics. We combine these field data with a field scale agro-hydrological model (Soil, Water, Atmosphere, Plant (SWAP)) (Kroes et al., 2017), calibrated to field data with PEST (Doherty, 2010). We simulate the hydrological consequences of CDSI systems on the longer term, focusing on wet, average and dry years. In this chapter, we focus on the water quantity effects of subirrigation on field scale. Water quality and water quantity at regional scales are not included.

3.2 Methods

3.2.1 Experimental sites

3.2.1.1 Characteristics field sites

CDSI was applied at four locations in the Dutch sandy Pleistocene uplands (Figure 3.2-I, II). The general set up of each drainage system is a control pit connected with a collector drain parallel to a ditch (Figure 3.2-III). The drainage pipes are placed perpendicular to the collector drain, at roughly 1.20 m-soil surface (ss) with 6 - 10 m spacing. At each site two piezometers are installed near and between two drains (Figure 3.2-III). The measurements are explained in detail in Figure 3.3 and described in section 3.2.1.2. Some specific geohydrological field characteristics are:

- Site A: grass and carrot field, the shallow groundwater level varies between 90-180 cm-ss and a resistant loam layer is present in the subsoil.
- Site B: grass field, the shallow groundwater level varies between 80-120 cm-ss. A loam or resistant layer is not present in the subsoil.
- Site C: grass field, the shallow groundwater level is relatively deep (100-230 cm-ss). Different loamy layers are present in the subsoil.
- Site D: maize and grass field, the shallow groundwater level is relatively shallow (25-100 cm-ss). Different loamy layers are present in the subsoil.

The main geohydrological characteristics of all sites are explained in Table 3.1. Site A is used to describe the applied methods in detail. All sites are modelled in the same way to quantify the effect of CDSI systems on components of the water balance for different geohydrological characteristics.

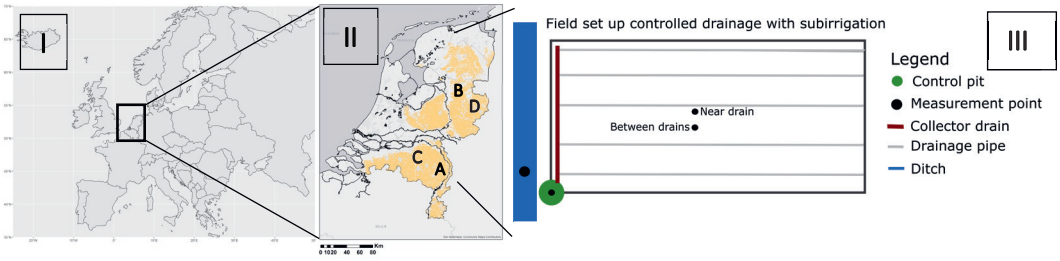


Figure 3.2: The Netherlands (I) with the (drought sensitive) sandy Pleistocene uplands (II, yellow) (0 – 100 m+MSL). The letters A, B, C and D represent the locations of the field experiments. III: Schematic field setup.

Table 3.1: (Geohydrological) characteristics of the four experimental field sites with CDSI systems (Figure 3.2). The average field height is also used as average soil surface in the field scale modelling.

		Site A	Site B	Site C	Site D
Source water supply		Groundwater	Surface water	Industrial effluent	WWTP effluent*
Location (town, coordinates)		America, 51º27'N, 5º57'E	Stegeren, 52º54'N, 6º51'E	Lieshout, 51º52'N, 5º62'E	Haaksbergen, 52º18'N, 6º71'E
Field area [ha]		3.77	2.5	8.5	5.85
Average field height [m+mean sea level (*MSL*)]		30.94	7.31	16.55	19.71
MxG	*MHG** [cm-ss]	~ 90	~ 80	~ 100	~ 25
	*MLG** [cm-ss]	~ 180	~ 120	~ 230	~ 100
Ditch level	Winter [cm-ss]	160	120	380	170
	Summer [cm-ss]	150	85	350	170
Crop		Grass (2017-2019) Carrot (2020) Grass (2021 – 2022)	Grass (2018-2022)	Grass (2015-2020)	Maize (2016-2020) Grass (2021-2022)
Soil		Sand, loam > 2-2.5 m-ss	Sand, loam - none	Sand, Loamy layers > 1-1.5 m-ss	Sand, Loamy layers > 3 m-ss
Time period		2017-2022	2018-2022	2015-2020	2016-2020
Includes reference field		Yes	Yes	No	No
Nearby KNMI station nr.		391	278	370	290

*WWTP: wastewater treatment plant, *MHG* = mean highest groundwater level, *MLG* = mean lowest groundwater level, KNMI = Royal Netherlands Meteorological Institute.

3.2.1.2 Set up measurements at the field sites

A schematic overview of a CDSI system including the drainage pipes, control pit, weir mechanism and ditch is given in Figure 3.3. The weir mechanism could be controlled online (site B and D) or manually (site A and C). All four field sites were equipped with measurement devices for: precipitation (duration and amount), water supply (flow), shallow and deep hydraulic head, *SMC* (and soil water potential (*SWP*) at site A) at 20, 40, and 60 cm depth, water level in the CDSI control pit and the ditch water level (Figure 3.3). At sites A and B also a reference field without drainage was equipped with measurement devices for: shallow and deep hydraulic head and *SMC* (and *SWP* at site A) at 20, 40, and 60 cm depth. The sensors in the reference field of site A and the *SWP* sensors at the subirrigation field of site A were installed in June 2021. Meteorological measurements were used from nearby weather stations from the Royal Netherlands Meteorological Institute (KNMI) (Table 3.1).

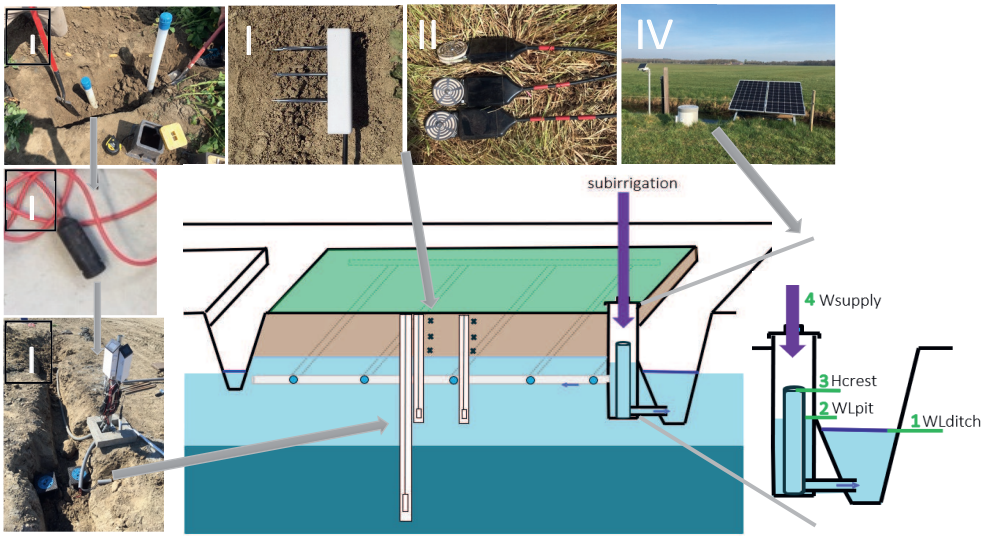


Figure 3.3: Schematization of a subirrigation system with the installed measurement devices. The drainage pipes are represented with dotted lines. Measurements are: shallow and deep hydraulic head (I), soil moisture content at 20, 40 and 60 cm depth (II), the soil water potential at 20, 40, 60 cm depth (III), the ditch water level (1, 'WL_{ditch}') and pit water level (2, 'WL_{pit}'), height of the fixed or online controlled weir in the pit (3, 'H_{crest}'), and the water supply (4, 'W_{supply}') (IV).

3.3 Field scale modelling

3.3.1 Field scale model SWAP

The agro-hydrological 1D-model Soil, Water, Atmosphere and Plant (SWAP) (Kroes et al., 2017) has been developed to simulate the transport of water, solutes and heat in the vadose zone, in interaction with crop development (Kroes et al., 2017). SWAP simulates the vertical transport (1D) of water in the vadose zone in interaction with crop development, including rooting depth and root water uptake. SWAP is briefly described in this section, a detailed description can be found in Kroes et al. (2017). Most important input parameters are the meteorological conditions, soil physical parameters (Van Genuchten, 1980), hydrological head in the underlaying aquifer, crop rooting depth, critical soil water pressure heads for root water uptake development and the lateral drainage situation. The simple crop development module is used for all simulations, which means that rooting depth and plant cover are input, while root water uptake (according to Feddes (1982)), is simulated dynamically. SWAP calculates, among other things, the hydrological fluxes (interception, evaporation, transpiration, seepage, infiltration and drainage), *GWL*, *SMC*, and crop stress (drought and oxygen stresses). Output could range from 15 minutes to years; here we use daily output.

SWAP contains different boundary conditions to simulate the soil water movement, as also schematically depicted in Figure 3.1. The upper boundary condition is given by the atmospheric precipitation and potential evapotranspiration. The simple crop module is a static crop represented as a green canopy that intercepts precipitation, transpires water vapor and shades the ground (Kroes et al., 2017). Main input variables are crop height, rooting depth, soil cover fraction, root length density at different depths in the root zone and crop sensitivity to drought and oxygen stress (Feddes, 1982). In the soil column, the soil hydraulic functions (soil moisture characteristic and hydraulic conductivity function) govern infiltration and soil evaporation at the top and soil moisture redistribution in and below the root zone. The lower boundary condition is represented as bottom flux (upward and downward seepage in Figure 3.1) calculated from the hydraulic head in the underlaying aquifer, the resistance to downward flow and the hydraulic head in the shallow aquifer. The hydraulic head in the underlaying aquifer is specified as sine function and is calibrated in this study (section 3.3.3). The side boundaries determine lateral drainage. The lateral drainage flux is incorporated in the numerical solution to the Richards equation as sink term (Kroes et al., 2017). Lateral drainage (i.e. the groundwater- surface water system) is included as a hierarchical system of different drainage levels. Drainage can be modelled via i) the basic drainage option when surface water levels are fixed and ii) via the extended drainage option to calculate dynamic water levels. The 'first order drainage system' is used to simulate ditch drainage and infiltration (Figure 3.1), for which ditch water levels (WL_{ditch}, Figure 3.3) are input and for which the drainage resistance is calibrated (section 3.3.3). The 'secondary drainage system' is used to simulate CDSI with subirrigation, as further described in section 3.3.2. More details are given in Kroes et al. (2017). Input files *.swp, *.dra and grassS.crp (including soil hydraulic functions, schematization of the lateral drainage, crop characteristics and root water uptake) for SWAP-simulations used in this study are included in the online supplementary material.

3.3.2 Controlled drainage with subirrigation in field scale model SWAP

CDSI systems can be modelled in SWAP via either the basic or the extended drainage module. Basic drainage is used when the water level in the pit (WL_{pit}, Figure 3.3) is fixed or given as input from measurements. As already mentioned, WL_{pit} is determined by the interplay between the height of the fixed or online controlled weir in the pit (H_{crest}, Figure 3.3), water supply (W_{supply}, Figure 3.3) and fluxes in the soil-groundwater-plant-atmosphere system. A fixed or constant WL_{pit} can only be reached when incoming fluxes exceed the total of the outgoing fluxes. In practice, however, the assumption of a constant WL_{pit} does not hold, as W_{supply} might be limited. This results in a dynamic WL_{pit}. The extended drainage option in SWAP allows for the dynamic simulation of WL_{pit}, using the controlled drainage system as the 'secondary drainage system' of the extended drainage module. For all simulations, the extended drainage option is used, either with WL_{pit} as input (calibration) or dynamic simulation of WL_{pit} (validation and application) (Figure 3.4).

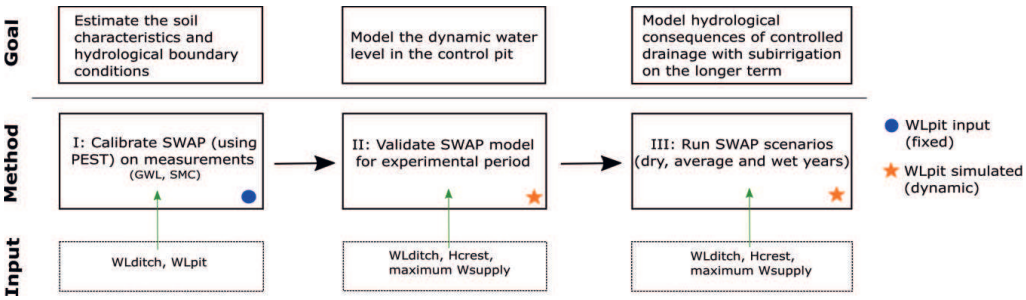


Figure 3.4: The goals of SWAP-modelling with the corresponding methods, and used boundary conditions to model the hydrological consequences of controlled drainage with subirrigation based on field measurements.

3.3.3 Calibration SWAP model with PEST

For each experimental site, SWAP (version 4.0.1) is calibrated using PEST (Doherty, 2010) to fit the input parameters with the local conditions of the field site (Table 3.1, Figure 3.4). The calibration methodology is described in detail as offline calibration in Bartholomeus et al. (2015b) using the method of Visser et al. (2006). In this approach, soil physical characteristics and system characteristics determining vertical and lateral drainage fluxes are optimized between a realistic range of values (based on literature), such that the (multiple year) time series of measured groundwater levels and soil moisture contents are approached. Possible changes in time of soil physical characteristics and drainage resistances are not considered.

The calibration is based on the measured *GWL* and measured *SMC* at three depths per field site. Other input is the precipitation and reference evapotranspiration according to Makkink (1957) obtained from the nearest KNMI weather station. Measured water levels in the control pit are input (i.e. no dynamic simulation of WL_{pit}). All time series data are available on daily basis.

The calibration is performed in two steps to reduce the number of variables that are calibrated simultaneously. The first calibration aims to estimate the soil physical parameters of the first two soil layers: saturated vertical hydraulic conductivity (KSAT), shape parameter alfa of main drying curve (ALFA), shape parameter n of Van Genuchten (1980) (NPAR), and the hydraulic head in the underlaying aquifer (AQAVE). Only the periods with accurate WL_{pit} measurements are used in the first calibration (Table 3.3). The second calibration aims to estimate the average vertical resistance (RIMLAY; affecting seepage fluxes) and drainage / infiltration resistances (RDRAIN1, RDRAIN2, RINFI2; affecting lateral drainage fluxes to the surface water and the CDSI system) and is based on the entire period of measurements per field site (Table 3.1). Since drainage/infiltration resistances might change over time (Bartholomeus et al., 2018b), the average resistances over the measurement period per field site are used in this chapter. The calibrated parameters of calibration 1 are input for calibration 2. All other conditions of the model are the same.

The calibration is evaluated on the goodness of simulated values compared to observed values of *GWL* and *SMC* using root mean square error (RMSE), RMSE-observations standard deviation ratio (RSR), and the Kling-Gupta efficiency (KGE). The goodness of calibrated parameters is evaluated with the dimensionless index for the range of confidence intervals called coefficient of variation (CV) (Doherty, 2004). The RSR includes a normalization factor, so that the index can be applied to various constituents (Moriasi et al., 2007). However, RSR gives more weight to high values when compared with low values (Moriasi et al., 2015). The RSR varies between the optimal value 0 to a large positive value (Moriasi et al., 2007). The commonly used and easy to interpret statistic RMSE has an optimal value of 0 (Moriasi et al., 2007). Finally, the KGE expresses the similarity between observed and simulated values (Gupta et al., 2009). Positive KGE values (with a maximum of 1) express good model performance, negative KGE values express bad model performances (Knoben et al., 2019).

3.3.4 Validation field model SWAP with dynamic simulation WL_{pit}

Validation of the calibrated model with dynamic simulation of WL_{pit} is performed for the field measurements of all field sites. Input are WL_{ditch}, W_{supply} and H_{crest}. Input files *.swp, *.dra and GrassS.crp for field sites A, B, C, and D are provided as online supplementary material. The validation step aims to verify if the model is able to simulate the field conditions with the extra complexity of a dynamic simulation of WL_{pit} (needed as explained in section 3.3.2). The simulated WL_{pit} is compared to the WL_{pit} measurement using RSR, RMSE and KGE (explained in section 3.3.3).

3.3.5 Apply field model SWAP for scenario analysis

The validated SWAP model is used to extend the simulations to the longer period 1993 – 2021, based on the available meteorological conditions. All models have similar input, except for the calibrated parameters and hydrological boundary characteristics, which are based on local conditions of each field (Table 3.1). This way, the effect of differences in geohydrological characteristics on the functioning and hydrological consequences of CDSI can be identified.

Meteorological conditions of the nearest KNMI weather station of site A are used for all sites. Crop input is grass. Yearly water supply period is 1st April to 30th September, with W_{supply} = 4 mm d^{-1}. H_{crest} is set to -80 cm+ss without subirrigation and -50 cm+ss with subirrigation. All other input parameters are as default. Output (per day) is, among other things, the actual W_{supply}, WL_{pit}, water balance components and crop water stress (oxygen- and drought stress).

3.4 Results

In sections 3.4.1 and 3.4.2 we focus on measurements and modelling of field site A in detail, and we discuss field sites B, C and D more generally to demonstrate differences for the application of CDSI systems for different geohydrological conditions. All results of the other sites are included in Appendices 3.7.3.1, 3.7.3.2, 3.7.3.3, 3.7.3.4.

3.4.1 Field measurements

3.4.1.1 Precipitation and water supply

Precipitation ranges from 445 mm in 2018 to 768 mm in 2021 for site A (Figure 3.5A). The long term average yearly precipitation (1993 – 2021) for site A is roughly 733 mm. The precipitation deficit varies from circa 128 mm in July 2018 to -20 mm in June 2021 for site A. The long term average monthly precipitation deficit (1993-2021) for site A varies from + 25 mm in July to + 35 mm in June. The measurement period of 2018 can thus be considered as a very dry year, while 2021 is relatively wet.

Water supply for subirrigation occurs in the growing season from roughly April to October (Figure 3.5A). Total water supply at site A ranges from about 1000 mm in 2017 (first year of field experiment) to approximately 200 mm in 2020. This means an average water supply of 4 mmd^{-1} in 2017 and 2018. The water supply between 2019 – July 2021 differs as explained in Appendix 3.7.1. Yearly water supply at field sites B, C, and D ranges from roughly 400 mm to 550 mm. Precipitation at all other sites is comparable to site A.

3.4.1.2 Groundwater level and soil conditions

The shallow groundwater level at the subirrigation field and the deep hydraulic head were similar in winter 2017 (Figure 3.5B). Furthermore, the reference shallow groundwater level, shallow groundwater level between drains and deep hydraulic head were similar in spring 2021, when water supply was almost zero. Therefore, the deep hydraulic head was interpreted as the reference situation for the years 2017-2020. The increased difference between the shallow groundwater level and the deep hydraulic head is the result of subirrigation.

The start of the water supply season is clearly visible in the measurements. The shallow groundwater level raises directly as water supply starts (Figure 3.5B). Water supply causes a raise of roughly 100 cm in 2021 (relatively wet year) to 150 cm in 2018 (relatively dry year). Similar results are found for site C. The groundwater level at field site B raises with around 30 cm. Because of groundwater level raise, the *SMC* in the root zone increases via capillary rise. *SMC* at 60 cm-ss increases at the start of the water supply period in 2017 and 2018 (Figure 3.5C). This capillary rise effect is less at 40 cm-ss and smallest at 20 cm-ss (Figure 3.5C). *SMC* at all three depths at field sites C and D increases as a result of subirrigation. At field site B this effect is less pronounced. The *SWP* at 20 cm-ss at the subirrigation field A

varies between -250 hPa to 0 hPa vs -600 hPa to 0 hPa at the reference field. Thereby, the soil at both fields becomes wetter with depth, where the subirrigation field is wetter than the reference field. It indicates drier circumstances at the reference field at site A than at the subirrigation field from August 2021 onwards. *SWP* at 20 cm-ss increases mid-September 2021 at both the reference field and the CDSI system field because of sprinkler irrigation.

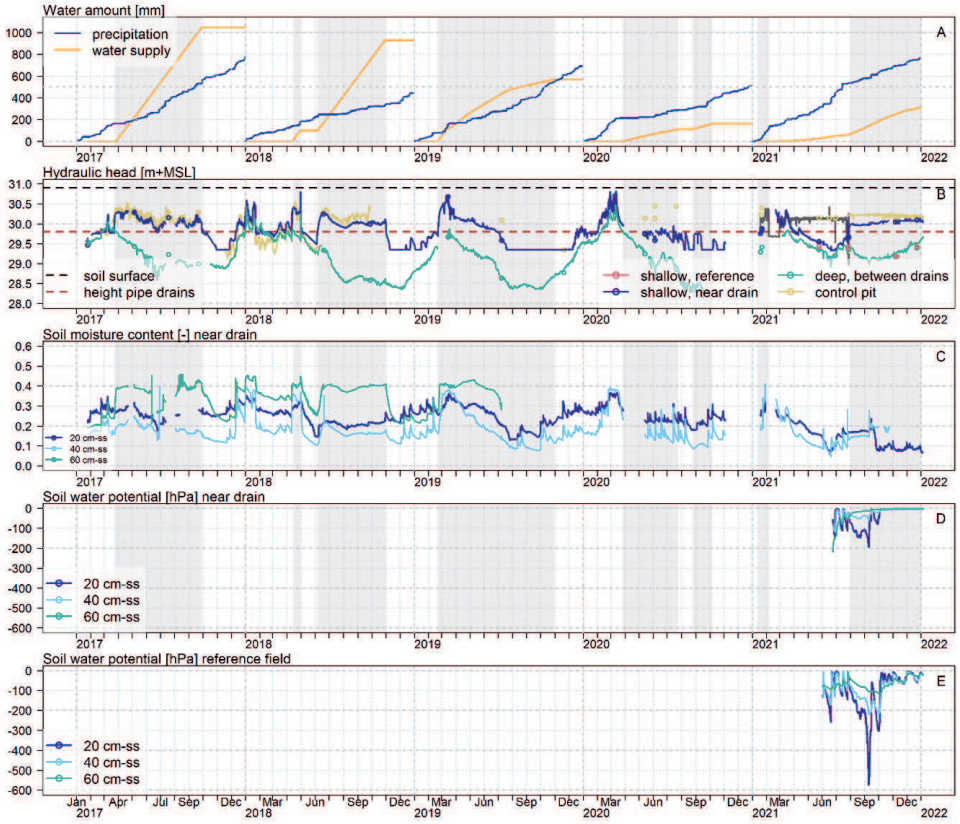


Figure 3.5: For site A holds: Precipitation from the automatic KNMI station Arcen and the water supply (A). Shallow groundwater level at the reference field and near the drain, deep groundwater head and water level in the control pit (B). The water level in the control pit is partly grey, as it is a period of clogging (2020-July 2021, see Appendix 3.7.1). Soil moisture content at 20, 40, 60 cm depth between drains (C). Soil water potential between drains (D) and at the reference field (E). The grey blocks represent the period of water supply. Soil water potential measurements and groundwater level at the reference field are only available in 2021.

3.4.2 Field scale model calibration

The simulated groundwater levels and *SMC* from the calibrated SWAP models of field site A (Figure 3.6) and C are both slightly higher and slightly lower throughout the years than the field measurements. Results from the calibrated SWAP model of field site B are comparable to the measurements of field site B. Simulated groundwater levels and *SMC* from the calibrated model of field site D are slightly lower than the field measurements of field site

D. Subtle differences occur between measurements and model results due to differences in modelling concepts and reality and because the calibrated value represents an average value over the calibrated period while real values might differ over time, e.g. the drainage resistance (Bartholomeus et al., 2018b). Statistics show that the RMSE for groundwater levels is 26.3 cm on average for all sites, ranging from 18.9 cm (site A) to 34.7 cm (site C). The RMSE for *SMC* is 0.05 on average for all depths at all sites. Furthermore, the RSR shows low values, indicating low RMSE values (Table 3.2). Finally, the KGE ranges from 0.18 (site B) to 0.66 (site A) (Table 3.2). Overall, simulations reproduce measurements quite well for all sites as the RMSE, RSR and KGE values indicate an acceptable model simulation performance.

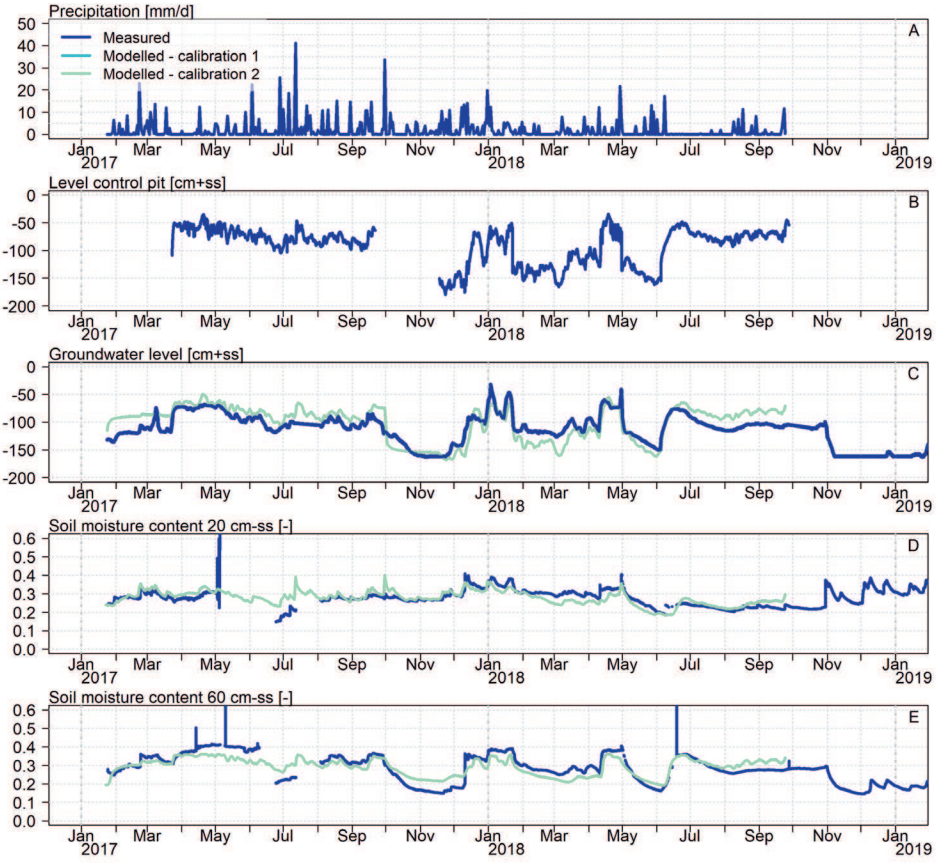


Figure 3.6: Field scale calibration SWAP with PEST with the goal to optimize the soil- and hydrologic parameters for the SWAP model for field site A. Calibration is based on the measurements: groundwater level and soil moisture at 20 cm and 60 cm-ss. Calibration 1 is behind the calibration 2 line. Measured precipitation at KNMI station Arcen (number 391) (input) (A), level control pit (input) (B), groundwater level (C), soil moisture content 20 cm-ss (D) and 60 cm-ss (E).

The CV of calibrated parameters ranges from 2.2% (site B) to 4.8% (site A). The average CV of all sites is 3.6%. Small CV values (Table 3.4) show that the optimized parameters are estimated accurately (the 95% confidence interval is small).

Table 3.2: Calculated statistics root mean square error ('RMSE'), RMSE-observations standard deviation ratio ('RSR') and Kling-Gupta efficiency ('KGE') for calibration SWAP with PEST for calibration 2 ('cal2'). Input is groundwater level ('GWL') and soil moisture content at 20, 40, 60 cm depth ('SMCXX'). SMC40 measurements are not used for sites A and C, because they are not reliable.

	Site A			**Site B**			**Site C**			**Site D***		
Parameter	RMSE	RSR	KGE	RMSE	RSR	KGE	RMSE	RSR	KGE	RMSE	RSR	KGE
***GWL*.cal2**	18.87	0.78	0.66	20.47	1.52	0.18	34.69	0.97	0.48	31.25	1.14	0.32
***SMC*20.cal2**	0.038	0.76	0.59	0.037	0.92	0.59	0.056	1.34	0.24	0.050	0.76	0.60
***SMC*40.cal2**	-	-	-	0.035	1.00	0.49	-	-	-	0.090	1.19	0.33
***SMC*60.cal2**	0.046	0.64	0.58	0.030	1.14	0.40	0.058	0.90	0.37	0.051	1.46	0.23
WL_{pit}.val	34.33	1.11	0.25	27.80	1.14	0.49	44.78	1.47	0.12	38.02	0.89	0.29

**SMC* depth site D is not 20, 40 and 60 cm, but 10, 58 and 78 cm.

3.4.3 Field scale model validation

The simulated water supply corresponds to the measured water supply for all field sites, except in 2017 for field site A when slightly less water supply is modelled than measured (Figure 3.7A). The change from fixed drainage level (in the calibration) to a dynamic drainage level (in the validation) results in a smooth water level in the control pit (Figure 3.7C) followed by a smooth groundwater head (Figure 3.7D). The strong decline in the water level in the control pit and thus in the groundwater head after a water supply period is also modelled quite well. Contrary, the strong raise in the water level in the control pit and thus the groundwater head at the start of the water supply period is not reproduced by the model (Figure 3.7C). Nevertheless, both the modelled water supply and the level in the control pit and the groundwater level are comparable with the measurements (Figure 3.7B, C, D). Furthermore, the modelled *SMC* at 20, 40, and 60 cm-ss is comparable to the measurements (Figure 3.7E, F, G). The RMSE of WL_{pit} is 36.2 cm on average for all sites, ranging from 27.8 cm (site B) to 44.8 cm (site C) (Table 3.2). The RSR is 1.15 on average for all sites, ranging from 0.89 (site D) to 1.47 (site C). The KGE varies between 0.12 (site C) to 0.49 (site B), with a mean of 0.29 for all sites. Overall, despite deviations in the water level in the control pit that affect the water supply, groundwater level and *SMC*, the model is still able to approach the hydrological conditions.

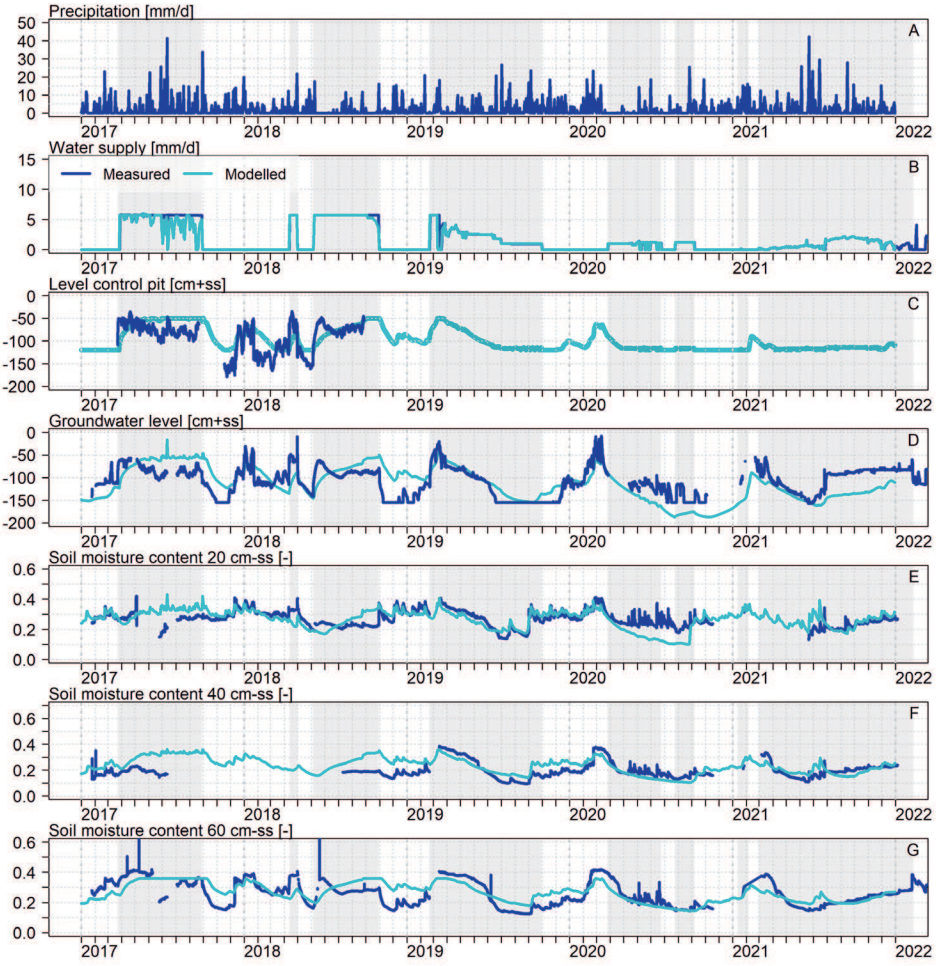


Figure 3.7: Validation of the calibrated SWAP model for field site A (2017-2021). Measured precipitation at KNMI station Arcen (number 391) (A), water supply (B), water level in the control pit (C), groundwater level (D), soil moisture content 20 cm-ss (E), 40 cm-ss (F), and 60 cm-ss (G). The grey blocks represent the period of water supply.

3.4.4 General hydrologic consequences of controlled drainage with subirrigation

The hydrological consequences of CDSI systems differ for a relatively wet, average and dry year. For site A holds:

- Wet year (Figure 3.8-I): yearly precipitation is roughly 1000 mm and water supply is roughly 580 mm. Water supply only occurred in the growing season (183 days). Of these days, 125 days were at a maximum water supply (4 mm d^{-1}), for 44 days water supply was between 0.1 – 4 mm d^{-1}, and for 14 days water supply was 0 as no additional water was needed to keep the water level in the control pit at the desired level. The water level in the control pit remains quite stable throughout the year. The *GWL* and *SMC* with subirrigation are clearly higher than without

subirrigation. Transpiration reduction due to drought stress is smaller with than without subirrigation. However, because transpiration reduction is already very small in the situation without subirrigation, subirrigation hardly contributes to an increased crop water availability.

- Average year (Figure 3.8-II): yearly precipitation was 650 mm and water supply was 700 mm. Water supply was not at the maximum water supply during 13 days. Compared to the wet year, it takes long to raise the water level in the control pit and *GWL* at the start of subirrigation period (77 vs 28 days respectively). The difference in *GWL* between simulations with and without subirrigation is larger than in a wet year. *SMC* is comparable with a wet year and quite stable throughout the year. However, because transpiration reduction is still small in the situation without subirrigation, subirrigation hardly contributes to an increased crop water availability.
- Dry year (Figure 3.8-III): yearly precipitation is 450 mm, water supply is 730 mm. Water supply is continuous at a maximum rate throughout the growing season. However, the maximum available water supply is not enough to raise the level in the control pit to the required 50 cm-ss. The water level in the control pit and *GWL* show a similar pattern, but the level is lower than in the average year. The *SMC* with subirrigation is higher than without subirrigation. Actual transpiration is more than 100 mm higher due to subirrigation. However, potential transpiration is not reached. This shows that subirrigation in the dry year and with the given maximum water supply rate, was not enough to stabilize the water level in the pit and thus the groundwater level, resulting in some crop stress in July and August.

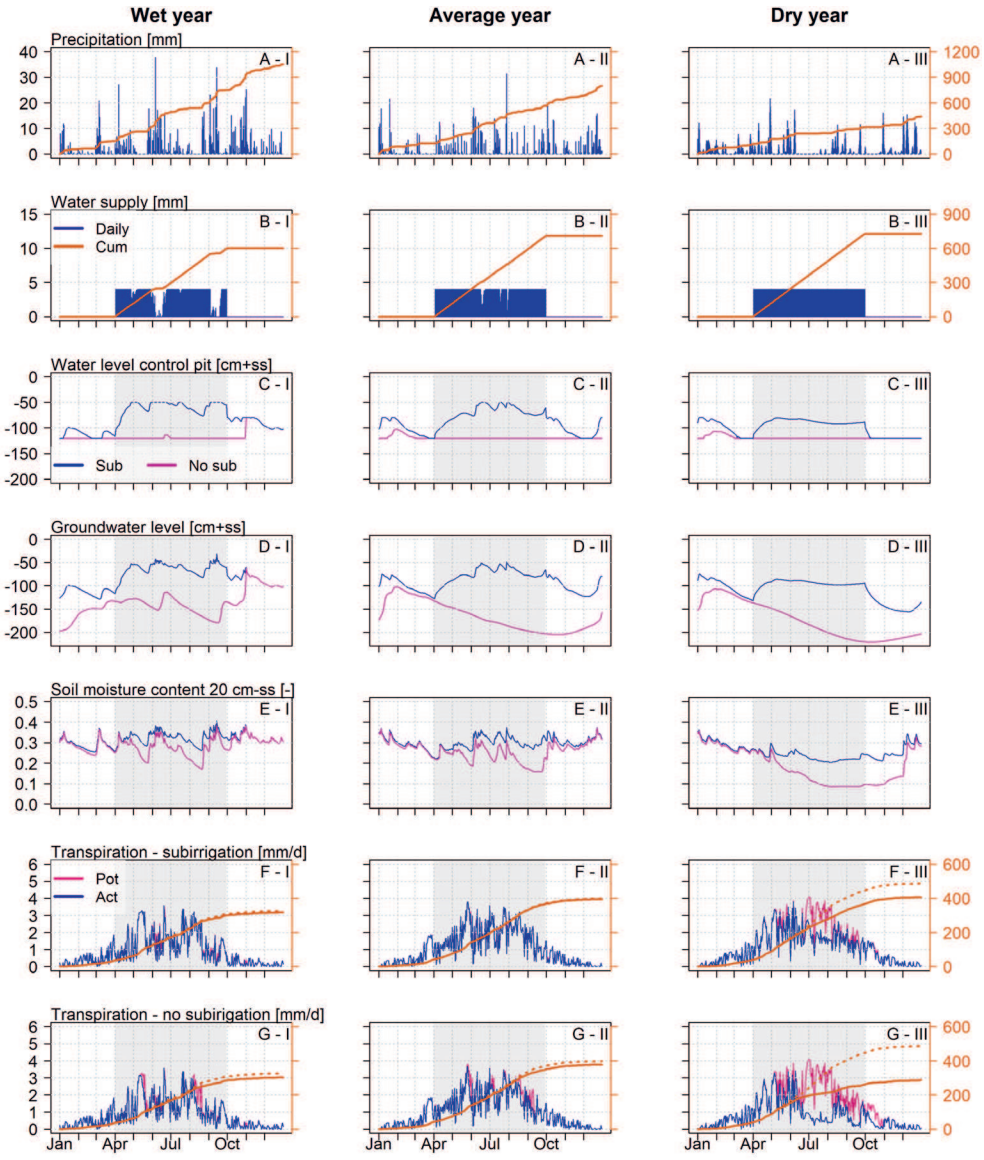


Figure 3.8: Hydrological consequences of controlled drainage with subirrigation for a wet year 1998 (I, left side), an average year 2012 (II, middle) and a dry year 2018 (III, right side), as modelled with SWAP for field site A. Precipitation (input, A), water supply (modelled, B), water level in the control pit (modelled, C), groundwater level (modelled, D), soil moisture content at 20 cm-ss (modelled, E), and potential and actual transpiration for a field with subirrigation (modelled, F) and a field without subirrigation (modelled, G). Precipitation and water supply are given on daily ('Daily') base and cumulative ('cum') amounts. Transpiration is given in cumulative potential transpiration (dotted, orange lines) and cumulative actual transpiration (solid, orange lines). Water level in the control pit, groundwater level, and soil moisture content at 20 cm-ss are given for a situation without subirrigation ('no sub') and with subirrigation ('sub'). The grey blocks represent the subirrigation period (1st April – 30th September).

3.4.5 Changes in the water balance due to subirrigation for four geohydrologic field sites

Water balance components (Figure 3.1) are strongly affected by subirrigation (Figure 3.9). Changes in the water balance also depend on the meteorological conditions (wet, average or dry year). Importantly, impacts of CDSI systems on components of the water balance are determined by the geohydrological characteristics of a field. The main changes in the water balance between a subirrigated field and a field without subirrigation are:

- Pipe infiltration increases through subirrigation. The simulated subirrigation varies between 390 - 600 mm in a wet year (site D vs site A) to 664 – 728 mm in a dry year (site D vs site A, dry) per growing season (183 days, April – September).
- The actual transpiration increases through subirrigation, but is strongly related to the depth of the groundwater level in relation to the rooting depth and soil properties (site specific). Capillary rise from the groundwater and rooting depth must be such that the soil water pressure head in the rooting zone is raised, resulting in an increase in root water uptake and actual transpiration. The increase in actual transpiration varies between 38 mm - 206 mm in a dry year (site B vs site C) to 0 – 14 mm in a wet year (site B vs site A). Subirrigation causes a shallower groundwater level, increasing root water uptake and crop growth.
- Downward seepage increases through subirrigation. Downward seepage increases with 131 mm – 640 mm in an average year (site C vs site B) and with 135 mm – 496 mm in a wet year (site C vs site B).
- Ditch drainage increases through subirrigation. Ditch drainage increases with 38 mm – 274 mm in an average year (site B vs site C) and with 147 mm – 336 mm in a wet year (site B vs site A). Ditch drainage occurs as the shallow groundwater level is higher than the ditch level. When subirrigation is applied, a higher shallow groundwater level will occur. Therefore, as ditch levels are kept the same, more drainage will occur. This means that water level regulation in the adjacent ditches is important to avoid unnecessary drainage.
- The exact annual effects of subirrigation on the water balance components depend on e.g. the growing season, crop development and soil moisture deficit (Figure 3.9).

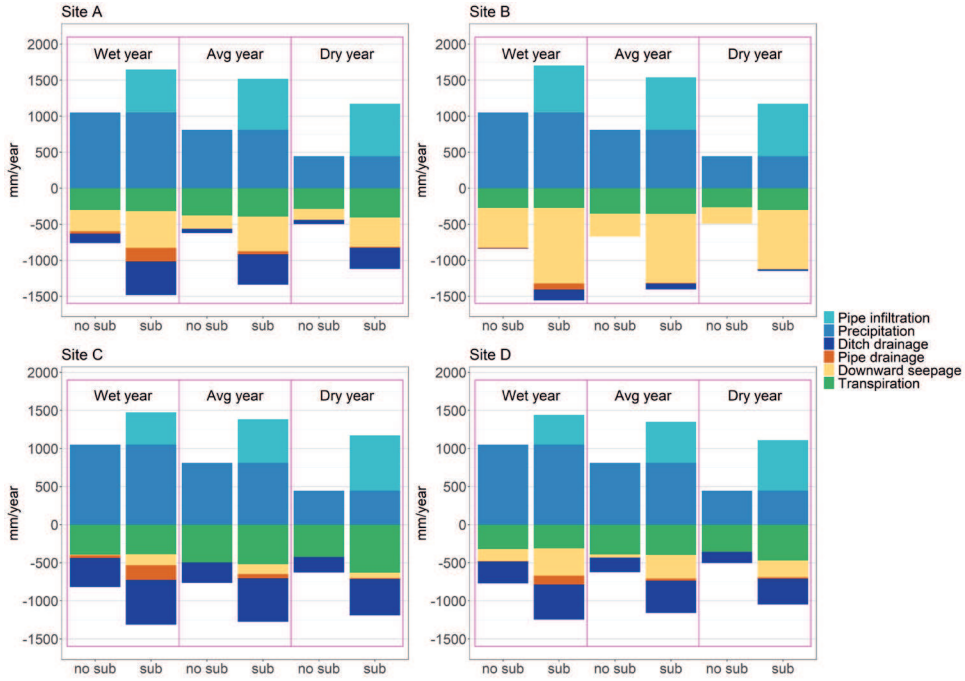


Figure 3.9: The modelled water balance components with the calibrated SWAP models for the experimental sites. All components are calculated for a wet year (1998), average year (2012) and dry year (2018) for a situation without water supply ('nosub') and with water supply ('sub'). Cumulative transpiration increases with on average 0% in wet years (-2.4% - 2.4%, site A vs site D), 1.8% in average years (0.18% – 3.54%, site B vs site C), and 16.9% in dry years (5.3% - 28.4%, site B vs site C), due to subirrigation ('pipe infiltration').

Part of the water supply results in a raise in *GWL* and an increase in *SMC* (Figure 3.5, Figure 3.7). Another part affects the water balance components (Figure 3.9). However, the distribution of water supply over the water balance components differs for each field site. Figure 3.10 shows the absolute changes in water balance components due to water supply for a wet, average and dry year.

- Field site A: most of the supplied water leaves the CDSI system as ditch drainage and downward seepage (46.8% vs 37.4%, on average). Drainage increases more in wet years compared to dry years (56.0% vs 33.0%), and transpiration increases more in dry years compared to wet years (16.5% vs 2.4%).
- Field site B: most water supply leaves the system as downward seepage (81.8%, on average). There is little ditch drainage (13.3%, on average). Transpiration especially increases in dry years (5%) and hardly in average years (0.2%).
- Field site C: water supply increases transpiration (10%, on average) and ditch drainage (46.3%, on average). The largest increase in transpiration is in the dry year (28.4%). A part of the supplied water leaves the system as downward seepage (21.5%, on average), as a resistance layer is present in the shallow underground. The remaining water supply leaves the system as pipe drainage (15.8%, on average).

- Field site D: water supply leaves the system as downward seepage (44.9%, on average), ditch drainage (38.9%, on average), and pipe drainage (11.9%, on average). Transpiration increases in the dry year (17.3%) and in the average year (1.0%).

The distribution of water supply over the water balance components differs strongly for all four sites. The geohydrological characteristics of the field site locations are the most important factor (Table 3.1). A lack of a hydraulic resistant (loam) layer is the reason for the large amount of downward seepage at location B. All other field locations have small loam layers in the soil which limit downward seepage (Table 3.1). Furthermore, ditch drainage can be avoided when the ditch level follows the groundwater level. Finally, the original mean highest and lowest groundwater level are relatively deep at field site C. Therefore, the groundwater raise as consequence of subirrigation has a large effect on the transpiration.

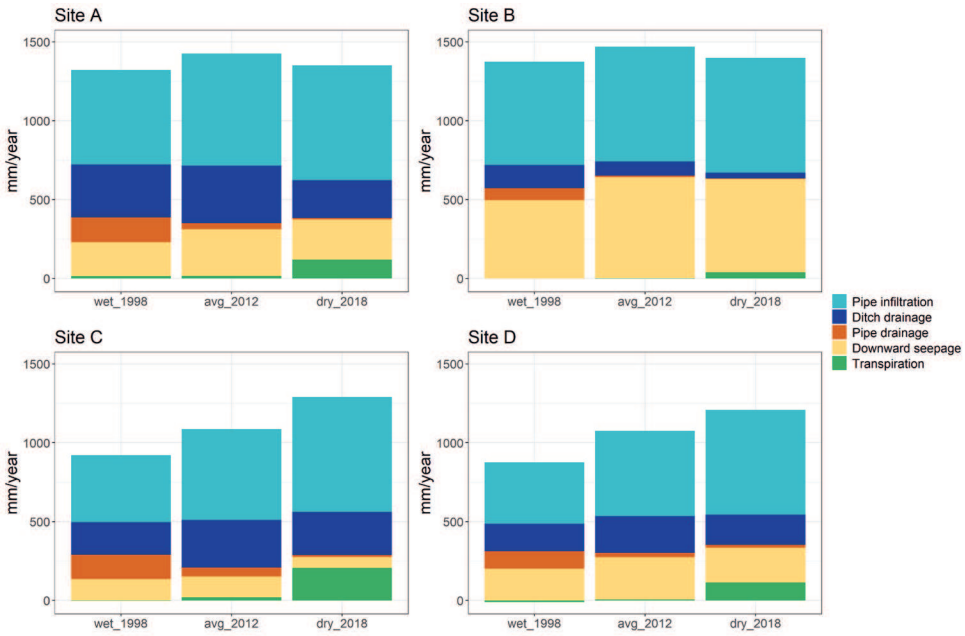


Figure 3.10: The increase in water balance components (ditch drainage, pipe drainage, downward seepage and transpiration) due to subirrigation ('pipe infiltration'). The amounts are based on the modelled water balance components with the SWAP model (with subirrigation minus without subirrigation). Wet = 1998, avg = 2012, dry = 2018.

3.5 Discussion

The experiments and analysis presented in this chapter are the first, to the best of our knowledge, that account for: i) comparable field set-ups of CDSI for different geohydrological characteristics on sandy soils, ii) including an agro-hydrological simulation

model to reproduce the field results and hydrological fluxes, and iii) dynamic simulation of the water supply rate and water level in the control pit. The dynamic simulation of water supply and pit water level adds complexity to the modelling approach of CDSI systems. However, it results in a better understanding of the functioning of CDSI systems.

The hydrological consequences of CDSI systems strongly depend on the local geohydrological characteristics. Even within an apparently uniform area like the 'higher sandy soils' of the Netherlands, subtle differences in regional and local geohydrological settings determine if CDSI improves crop water availability. As found in earlier literature (Singh et al., 2022) plant transpiration could increase by water supply through CDSI systems, but the effect varies within and between the growing seasons of different years, based on, amongst other things, crop type (e.g. with different rooting depths) and meteorological conditions (Figure 3.10). A literature overview on the effect of CDSI on groundwater level and yield is given in De Wit et al. (2022). Both this literature overview and the here presented field experiments show a raise of approx. 50 cm in groundwater level due to subirrigation. An increase of plant transpiration with 38 mm to 206 mm (14.7% to 48.6%) in our study in dry years (site B vs site C) and -9.2 mm to 14.5 mm (-2.89% to 4.8%) in wet years (site D vs site A) is roughly comparable to the reported literature (35% in dry years to 10% in wet years) (Allred et al., 2003) and 6% yield increase (Mejia et al., 2000; Wesström et al., 2014).

The total amount of water used for subirrigation could be large which significantly impacts local scale hydrological fluxes (Figure 3.10) and needs water supply capacity. Consequently, such a local scale measure could propagate through the regional water system. Therefore, subirrigation systems and operational management should be implemented in such a way that they fit within both the local and regional management (Figure 3.11) and that they match freshwater availability. The modelling procedure developed in this study could be used to identify appropriate field sites for CDSI application and the hydrological consequences before implementing subirrigation. All aspects related to drainage design, required water supply, and field scale impact could be modelled with SWAP. This includes explorations on the effect of subirrigation for different crops and crop characteristics. As example we analysed the effect of subirrigation for a rooting depth for grass of 50 cm instead of 30 cm (as used in this study; schematization of site A). This 20 cm increase in rooting depth increased plant transpiration in the dry year with 5.6%. The increase in transpiration results in a decrease in lateral drainage (-4.4%), downward seepage (-2.0%) and pipe drainage (-1.1%). This means a larger portion of the subirrigated water contributes to crop growth, while less water is drained to the groundwater and surface water system. Similar analysis could be done with e.g. drainage design (drain depth and drain spacing), water supply design (frequency, required drainage level and capacity), soil type, resistance to downward seepage, surface water management and crop type, for all

possible meteorological conditions (Figure 3.11). Required water supply and e.g. increased downward seepage (i.e. increased groundwater recharge) are relevant for the regional implementation of CDSI with subirrigation. The scheme presented in Figure 3.11 provides an overview of considerations to take into account.

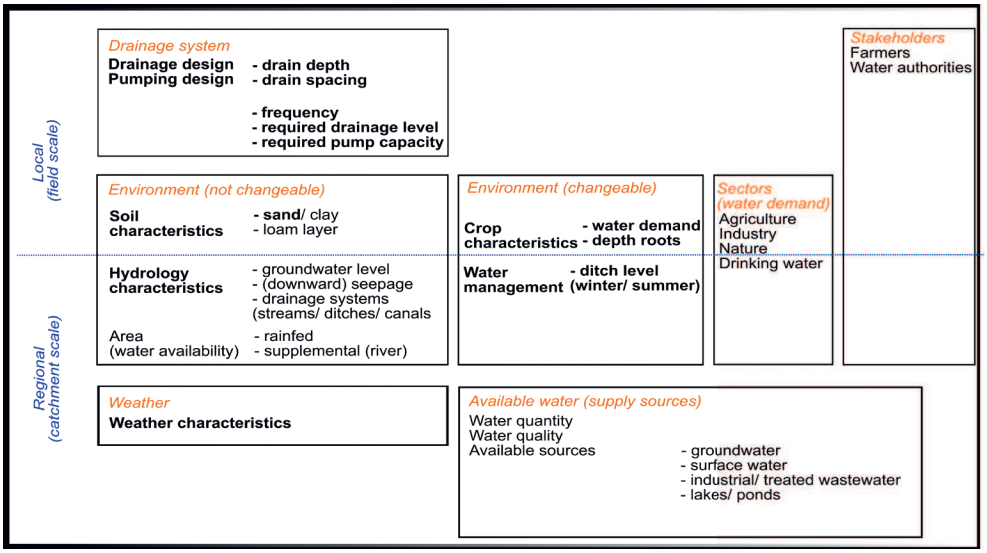


Figure 3.11: Overview of local and regional scale components to take into account when implementing controlled drainage with subirrigation. The components in bold are part of the field experiments and modelling analysis. Figure adapted from De Wit et al. (2022).

The agro-hydrological model SWAP was able to reproduce the field measurements of the CDSI system field experiments. Bottom boundary parameters and the drainage resistances were obtained by calibration for the local circumstances. Calibration ranges for the average hydraulic head in the underlying aquifer and the vertical resistance of the aquitard were set based on the piezometer measurements of the aquifer pressure head and literature on general regional characteristics (Van der Gaast, 2006). However, it is important to notice that the resistances for downward and lateral flow may complement each other and different combinations of resistances could lead to the same simulated groundwater levels. Therefore, field measurements and local geohydrological knowledge are required to set reliable calibration ranges, as done in this study.

Water was supplied daily in the growing season (roughly April to October), resulting in amounts of water supply ranging from approximately 500 mm to 1000 mm per season, which exceeds the annual precipitation surplus. However, the CDSI water supply strategy could be optimized to reach the intended drainage level, while minimizing the required water supply (Smith et al., 1985):

- Controlled drainage allows for water retention in winter and spring. The amount of water stored reduces the need for additional recharge. Water supply/ subirrigation could start later, or less water is needed to achieve the required groundwater level. To achieve this, the practical management operations by the farmer are of great importance, including balancing between too dry and too wet conditions in the root zone.
- Water supply could be optimized by supplying water only when crop transpiration is potentially reduced (Bartholomeus et al., 2015a; Smith et al., 1985). Field experiments show that groundwater levels respond quickly to subirrigation, which may allow for non-continuous water supply.
- Drainage losses to ditches can be avoided when the managed/ controlled level of surface waters equals or exceeds the groundwater level. For the Netherlands, this often requires coordination between farmers and the regional water management authority.

The field experiments and subsequent modelling confirmed that a soil layer with limited permeability is required to avoid or reduce extreme downward seepage losses by groundwater recharge (Skaggs, 1999; Yu et al., 2020). If e.g. loamy layers are present, CDSI could have positive effects even on sites with relatively deep groundwater levels in the situation without subirrigation, as demonstrated at site C. Using detailed information on soil properties and hydrological conditions combined with the dynamic modelling analysis as performed in this research, allows to decide on the feasibility of the measure in the explorative phase already, including estimations of the required water supply.

3.6 Conclusion

In agricultural fields CDSI systems could be a viable measure to i) retain, ii) recharge, and iii) discharge water. Doing so, CDSI contributes positively to operational groundwater level management for agricultural crop production and acts as an extension of CAD systems (Van den Eertwegh et al., 2013). However, this study showed that CDSI systems alter the hydrological fluxes significantly. Field measurements on four experimental plots showed that the water supply to CDSI systems can be high (ranging between roughly 500 mm to 1000 mm in the field sites), but CDSI systems are able to raise the groundwater level such that soil water availability for crops increases. However, simulations with the agro-hydrological model SWAP showed that the actual plant transpiration only strongly increases in dry years with the use of CDSI systems. For meteorologically average and wet years the differences between subirrigation and no subirrigation are less pronounced or even negligible. Comparison of the four experimental fields also showed that a resistance layer below the subsurface drains is needed to reduce downward seepage losses. Excessive downward seepage, or drainage losses towards surface water, increase the required water supply. However, unnecessary ditch drainage losses can be avoided by adapting the surface water level to the groundwater level.

Field experiments are required to understand the real-world situation better, leading to better models in terms of schematization, processes modelled, and model parameter values. This study showed that field pilots varying in geohydrological conditions could be modelled acceptably well using SWAP. SWAP could be calibrated using PEST and was able to reproduce the data of the field experiments with CDSI systems. Both the required water supply and the water level in the control pit of the CDSI system were simulated dynamically, which is a key element in understanding the functioning of CDSI systems. The process-based model results lead to insight in the water balance components, also those components that cannot be (easily) measured in the field, and in (extreme dry or wet) meteorological conditions that were not part of the experimental periods. The modelling procedure that we developed can support in the design of CDSI systems for a range of geohydrological settings, including quantification of required water supply rates for different management strategies of CDSI systems, crop characteristics and meteorological conditions. Although CDSI is a field-scale measure, the regional-scale freshwater availability for subirrigation will be an important factor for successful and sustainable CDSI implementation (De Wit et al., 2022).

3.7 Appendix

3.7.1 Appendix: Clogging field site A

A special situation occurred at field site A from 2019 to half 2021, caused by (iron) clogging of the drainage pipes (Figure 3.12, left). Infiltration rate decreased in this period (Figure 3.5A), resulting in a deeper groundwater level and lower soil moisture content (Figure 3.5B, C). The water level in the control pit remained high in 2020-2021, because water supply still occurred, but at a lower rate. However, because of the clogged drains, the supplied water could not enter the drainage pipes resulting in lower groundwater levels. The pipes were cleaned and some pipe parts were replaced in July 2021 (Figure 3.12, right). The water supply increased again in August 2021 (Figure 3.5A), followed by the groundwater level (Figure 3.5B).



Figure 3.12 Clogged drainage pipes (left) and a replaced part of the drainage pipe (right) at field site A on 27-07-2021

3.7.2 Appendix: Data used for two-step calibration

Table 3.3: Tstart and tend for two-step calibrations for field site A, B, C and D.

Field site		A	B	C	D
Calibration 1	Tstart	24-01-2017	01-11-2018	01-01-2016	01-01-2016
	Tend	24-09-2018	31-08-2022	31-05-2018	30-09-2017
Calibration 2	Tstart	24-01-2017	01-11-2018	01-01-2016	01-01-2016
	Tend	24-09-2018	31-08-2022	30-06-2020	30-12-2019

3.7.3 Appendix: Results calibration – validation – application

3.7.3.1 Field site A

a) Field site A – calibration

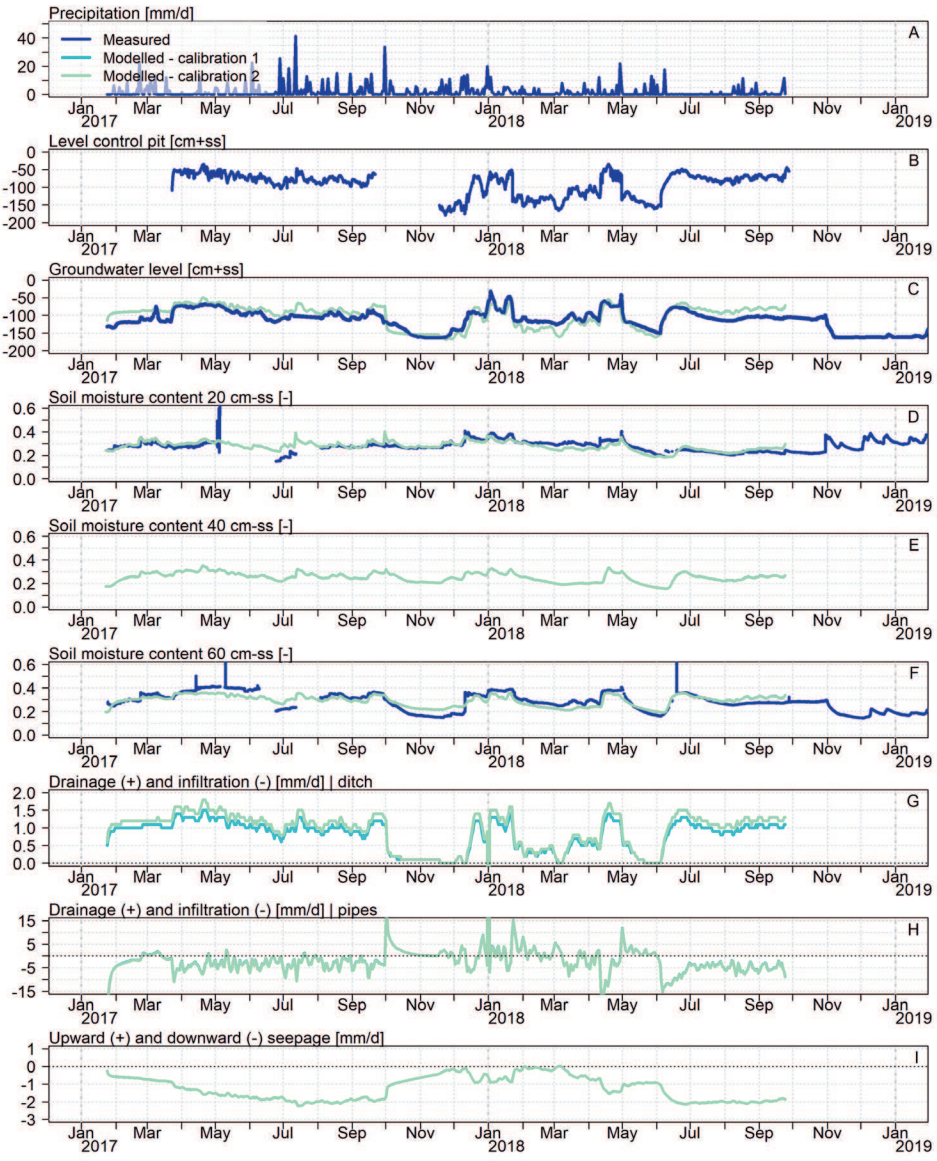


Figure 3.13: Field scale calibration SWAP with PEST with the goal to optimize the soil- and hydrologic parameters for the SWAP model for field site A. Calibration is based on the measurements: groundwater level and soil moisture at 20 cm and 60 cm-ss. Measured precipitation at KNMI station Arcen (number 391) (input) (A), level control pit (input) (B), groundwater level (C), soil moisture content 20 cm-ss (D), 40 cm-ss (E), and 60 cm-ss (F), drainage and infiltration of the ditch (G) and of the pipes (H), and upward and downward seepage (I).

*b) Field site A – validation (see *.swp and *.dra file in supplementary material)*

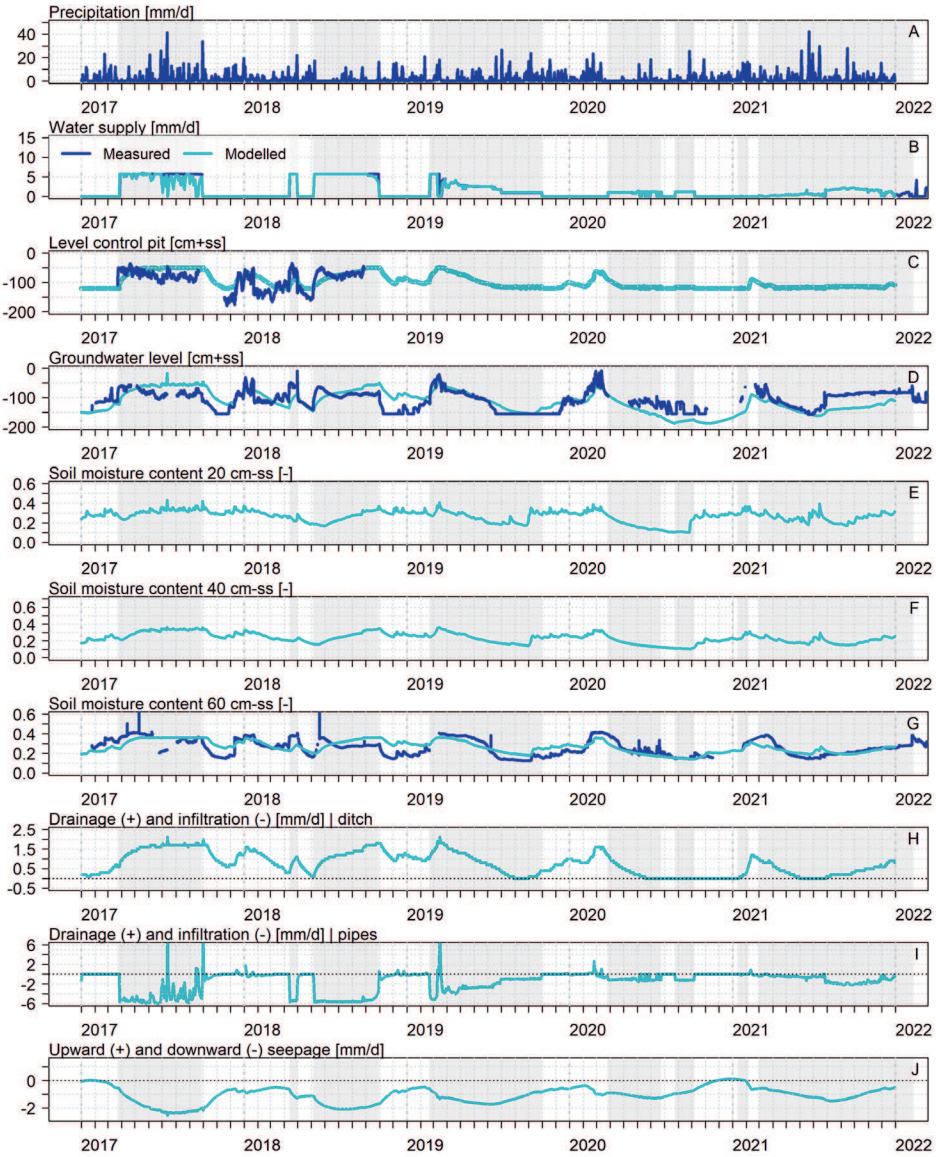


Figure 3.14: Validation with the calibrated SWAP model for field site A (2017-2021). Measured precipitation at KNMI station Arcen (number 391) (input) (A), water supply (B), level control pit (C), groundwater level (D), soil moisture content 20 cm-ss (E), 40 cm-ss (F), and 60 cm-ss (G), drainage and infiltration of the ditch (H) and of the pipes (I), and upward and downward seepage (J). The grey blocks represent the period of water supply.

c) Field site A – application

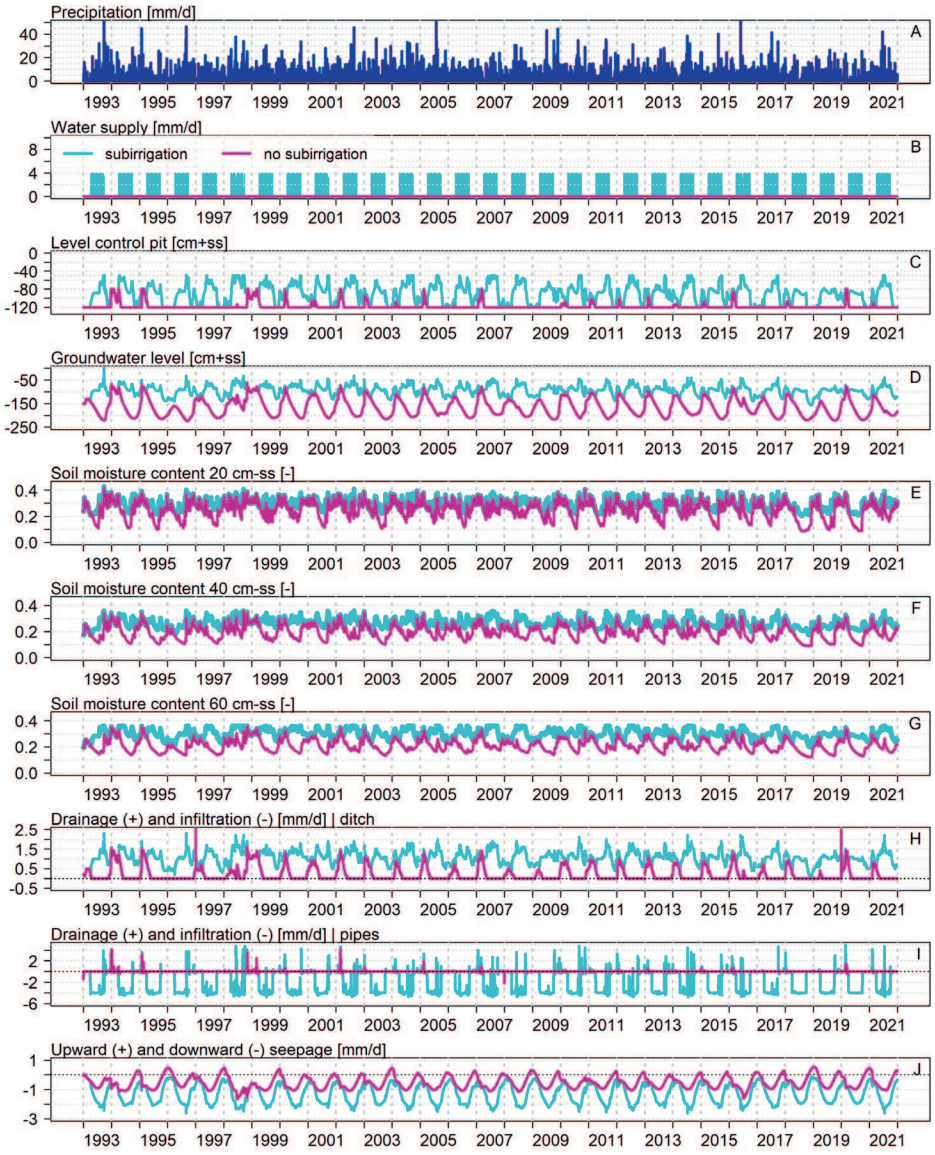


Figure 3.15: Application with the calibrated SWAP model for field site A. Measured precipitation at KNMI station Arcen (number 391) (input) (A), water supply (B), level control pit (C), groundwater level (D), soil moisture content 20 cm-ss (E), 40 cm-ss (F), and 60 cm-ss (G), drainage and infiltration of the ditch (H) and of the pipes (I), and upward and downward seepage (J).

3.7.3.2 Field site B

a) Field site B – calibration

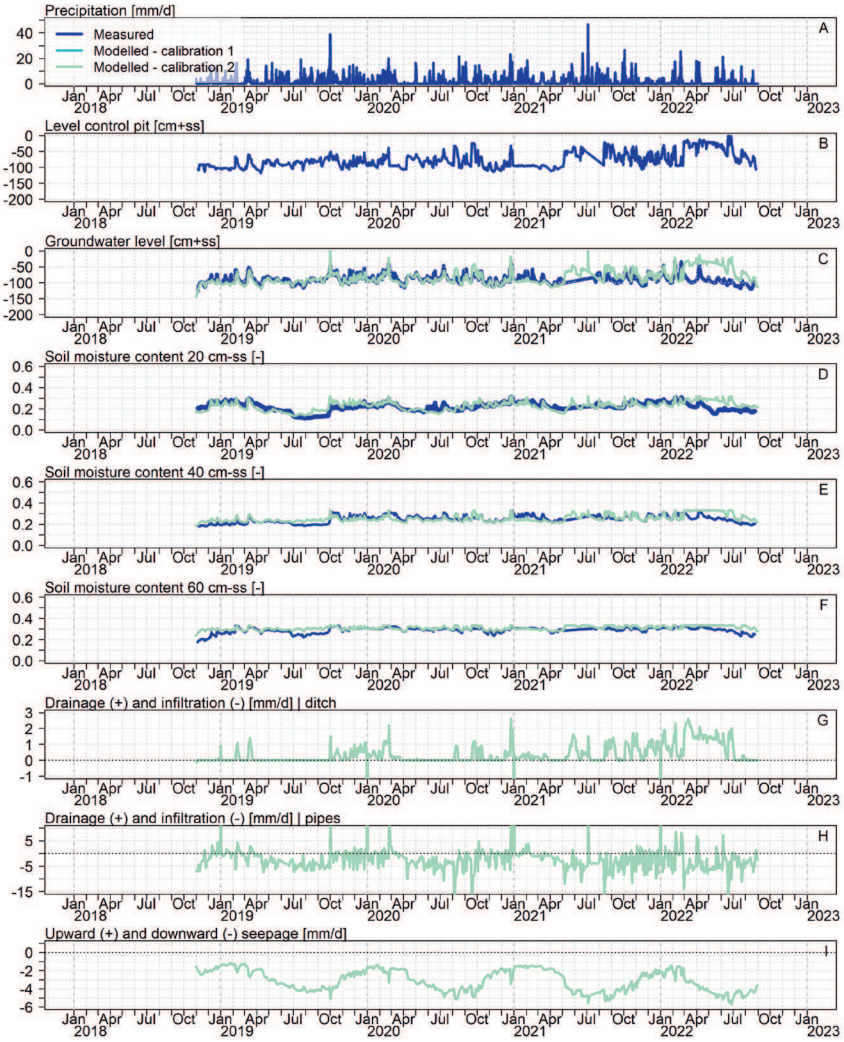


Figure 3.16: Field scale calibration SWAP with PEST with the goal to optimize the soil- and hydrologic parameters for the SWAP model for field site B. Calibration is based on the measurements: groundwater level and soil moisture at 20 cm, 40 cm and 60 cm-ss. Measured precipitation at KNMI station Heino (number 278) (input) (A), level control pit (input) (B), groundwater level (C), soil moisture content 20 cm-ss (D), 40 cm-ss (E), and 60 cm-ss (F), drainage and infiltration of the ditch (G) and of the pipes (H), and upward and downward seepage (I).

Remark: the groundwater level responds to the water level in the control pit. From 2022 onwards, the water level in the control pit raised because of a bigger pump. At the same time, the measured groundwater level did not raise. The piezometer and the control pit are actually located 200 meters apart. In the model, they are located within 6 meters of each other. It could be that in reality the pumped water has left the field as downward seepage before the water reaches the piezometer.

*b) Field site B – validation (see *.swp and *.dra file in supplementary material)*

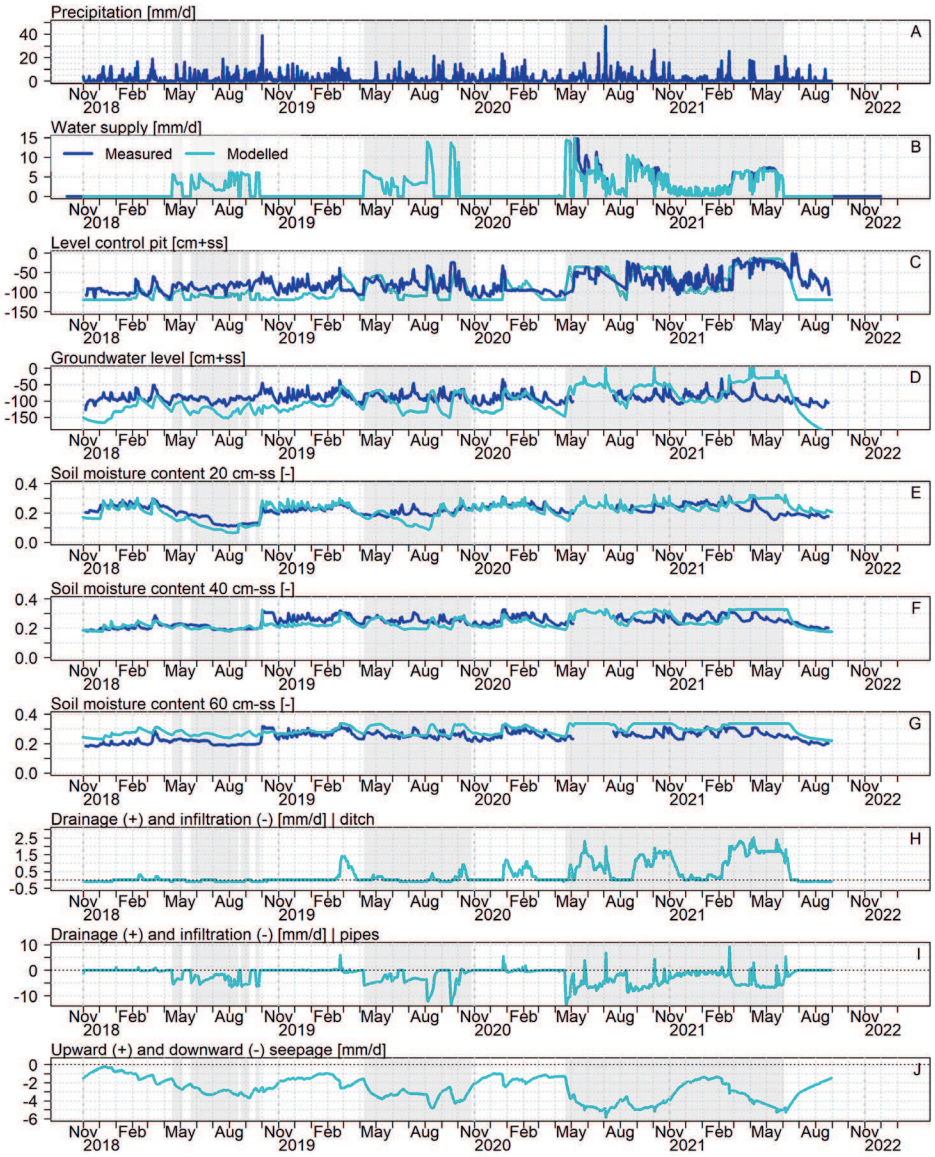


Figure 3.17: Validation with the calibrated SWAP model for field site B (2018-2022). Measured precipitation at KNMI station Heino (number 278) (input) (A), water supply (B), level control pit (C), groundwater level (D), soil moisture content 20 cm-ss (E), 40 cm-ss (F), and 60 cm-ss (G), drainage and infiltration of the ditch (H) and of the pipes (I), and upward and downward seepage (J). The grey blocks represent the period of water supply.

c) Field site B – application

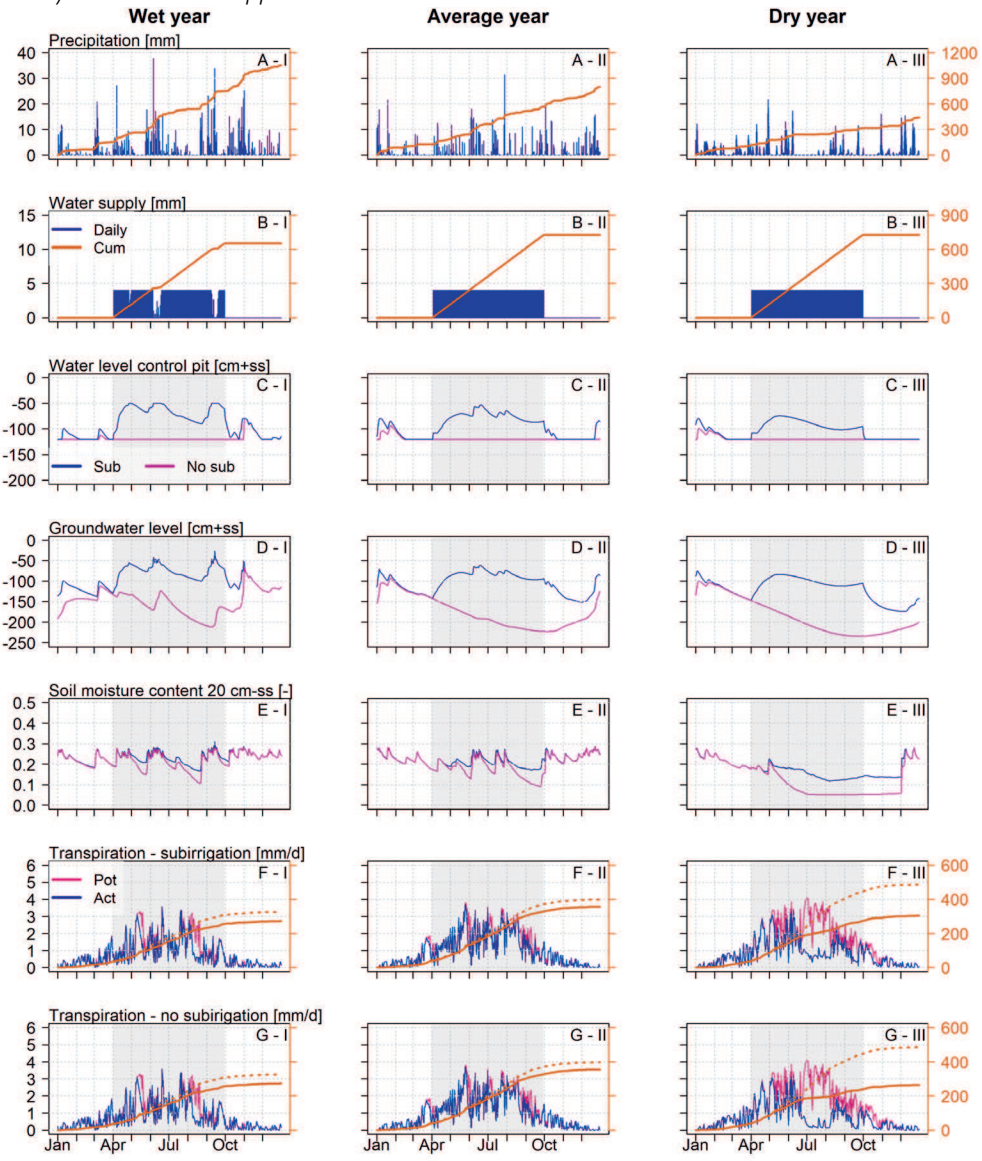


Figure 3.18: Hydrological consequences of controlled drainage with subirrigation for a wet year 1998 (I, left side), an average year 2012 (II, middle) and a dry year 2018 (III, right side), as modelled with SWAP for field site B. Precipitation (input, A), water supply (modelled, B), water level in the control pit (modelled, C), groundwater level (modelled, D), soil moisture content at 20 cm-ss (modelled, E), and potential and actual transpiration (modelled, F). Precipitation and water supply are given in daily ('Daily') base cumulative ('cum') amounts. Water level in the control pit, groundwater level, and soil moisture content at 20 cm-ss are given for a situation without subirrigation ('no sub') and with subirrigation ('sub'). The grey blocks represent the subirrigation period (1st April – 30th September).

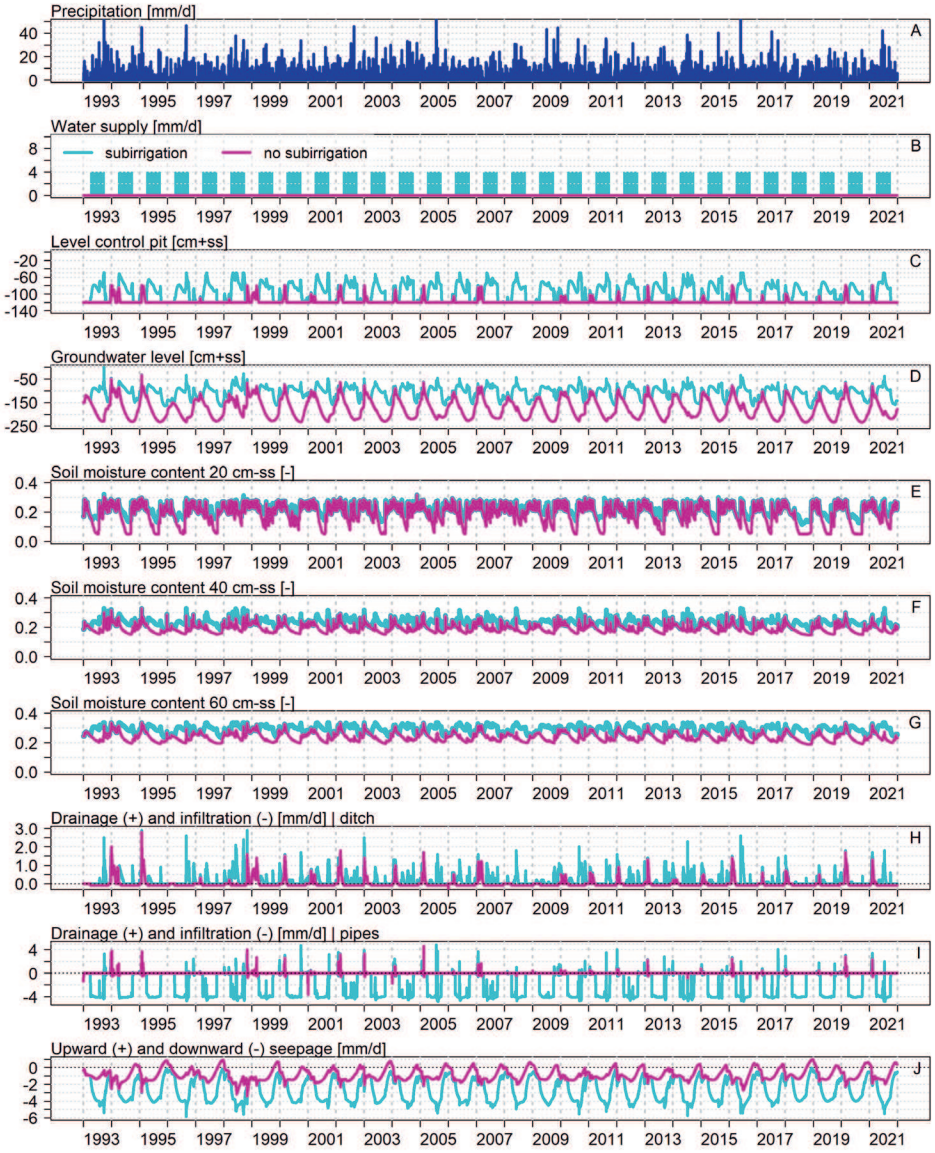


Figure 3.19: Application with the calibrated SWAP model for field site B. Measured precipitation at KNMI station Arcen (number 391) (input) (A), water supply (B), level control pit (C), groundwater level (D), soil moisture content 20 cm-ss (E), 40 cm-ss (F), and 60 cm-ss (G), drainage and infiltration of the ditch (H) and of the pipes (I), and upward and downward seepage (J).

3.7.3.3 Field site C

a) Field site C – calibration

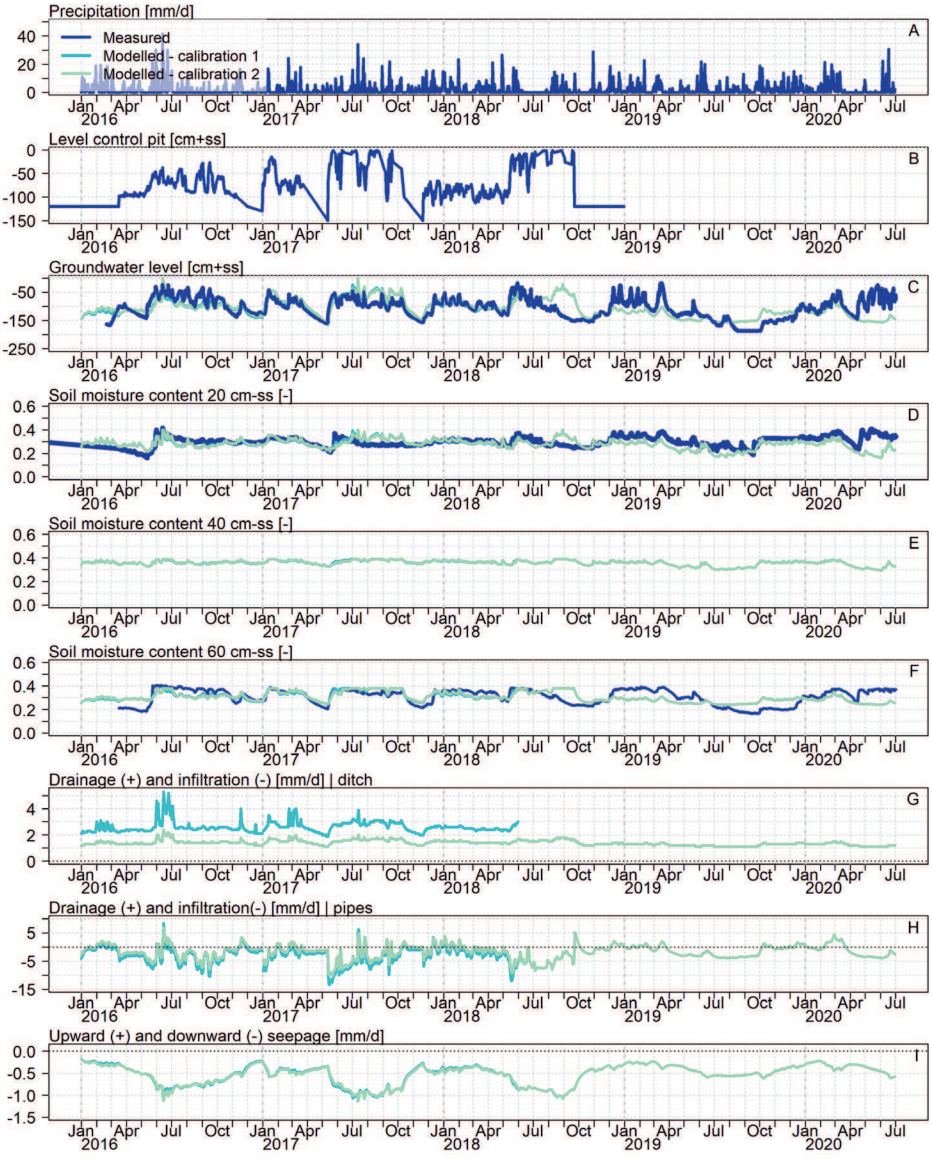


Figure 3.20: Field scale calibration SWAP with PEST with the goal to optimize the soil- and hydrologic parameters for the SWAP model for field site C. Calibration is based on the measurements: groundwater level and soil moisture at 20 cm and 60 cm-ss. Measured precipitation at KNMI station Eindhoven (number 370) (input) (A), level control pit (input) (B), groundwater level (C), soil moisture content 20 cm-ss (D), 40 cm-ss (E), and 60 cm-ss (F), drainage and infiltration of the ditch (G) and of the pipes (H), and upward and downward seepage (I).

*b) Field site C – validation (see *.swp and *.dra file in supplementary material)*

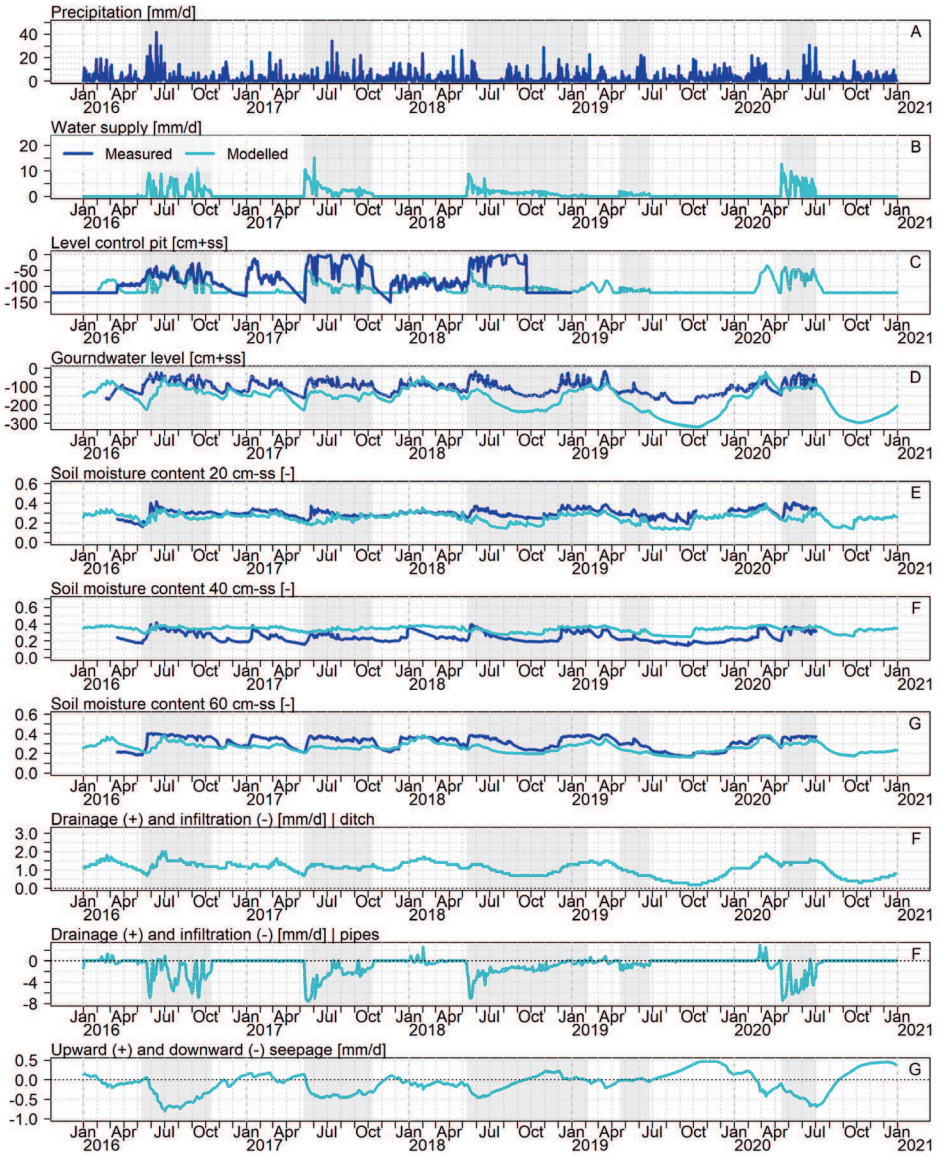


Figure 3.21: Validation with the calibrated SWAP model for field site C (2016-2021). Measured precipitation at KNMI station Eindhoven (number 370) (input) (A), water supply (B), level control pit (C), groundwater level (D), soil moisture content 20 cm-ss (E), 40 cm-ss (F), and 60 cm-ss (G), drainage and infiltration of the ditch (H) and of the pipes (I), and upward and downward seepage (J). The grey blocks represent the period of water supply.

c) Field site C – application

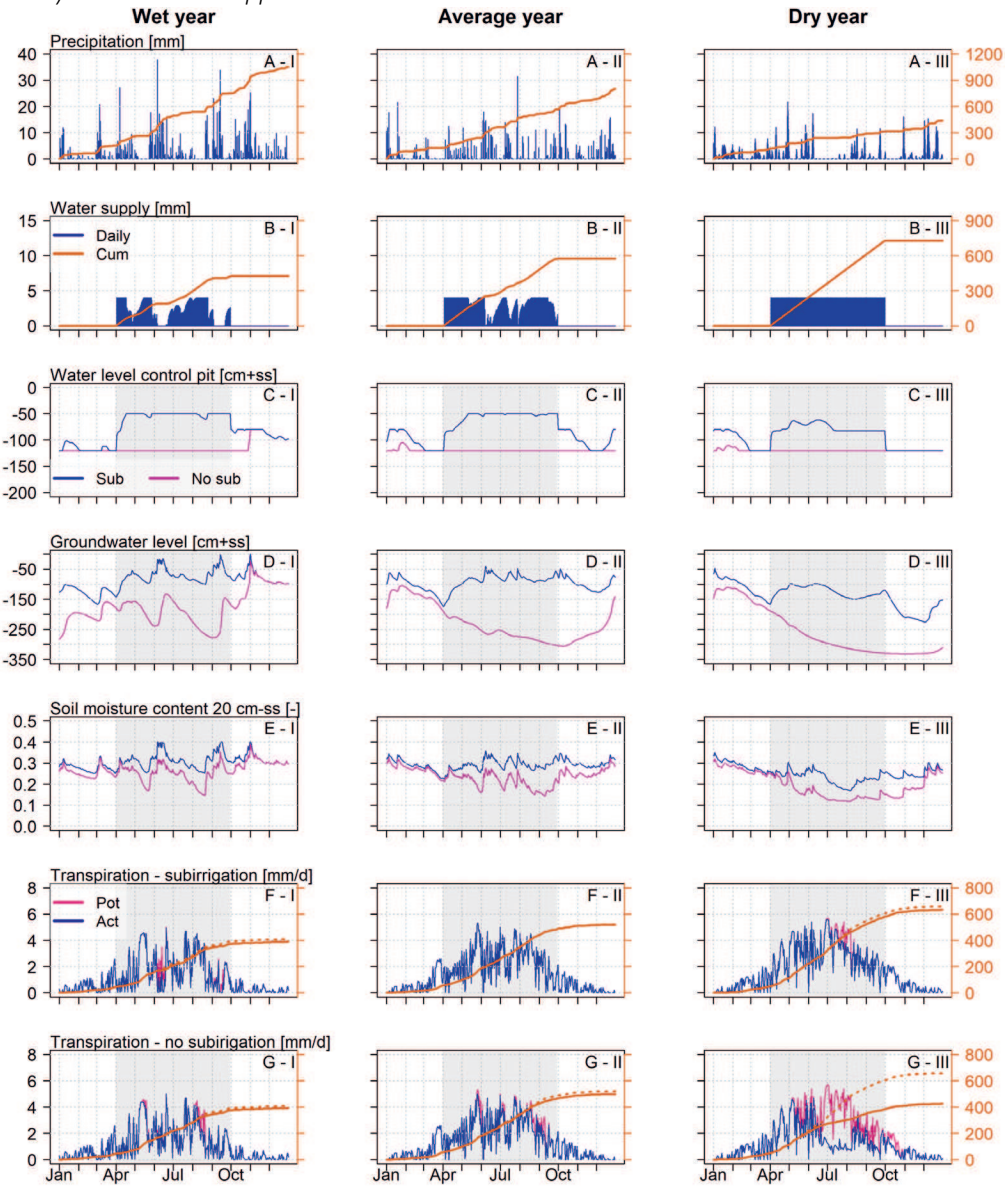


Figure 3.22: Hydrological consequences of controlled drainage with subirrigation for a wet year 1998 (I, left side), an average year 2012 (II, middle) and a dry year 2018 (III, right side), as modelled with SWAP for field site C. Precipitation (input, A), water supply (modelled, B), water level in the control pit (modelled, C), groundwater level (modelled, D), soil moisture content at 20 cm-ss (modelled, E), and potential and actual transpiration (modelled, F). Precipitation and water supply are given in daily ('Daily') base cumulative ('cum') amounts. Water level in the control pit, groundwater level, and soil moisture content at 20 cm-ss are given for a situation without subirrigation ('no sub') and with subirrigation ('sub'). The grey blocks represent the subirrigation period (1st April – 30th September).

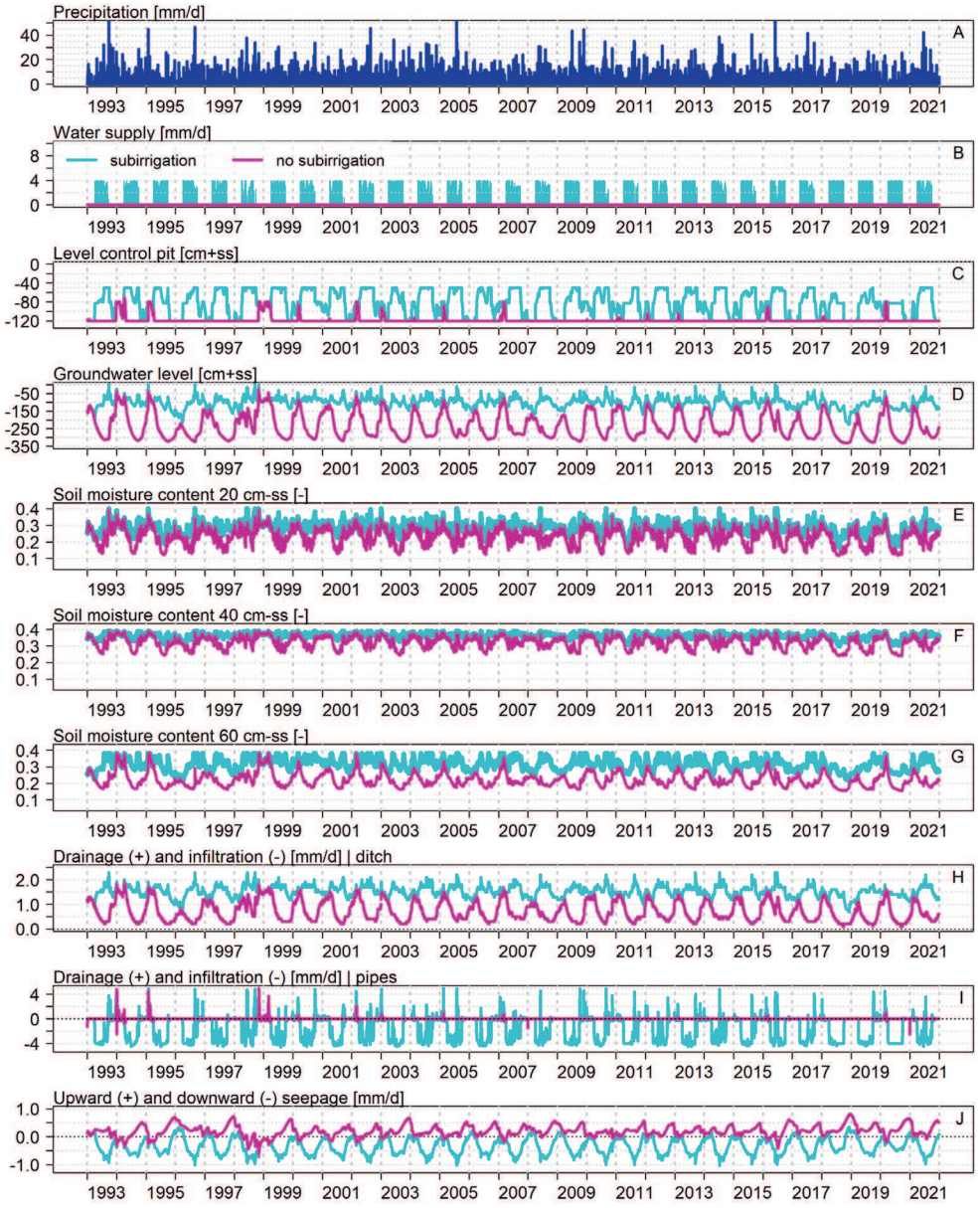


Figure 3.23: Application with the calibrated SWAP model for field site C. Measured precipitation at KNMI station Arcen (number 391) (input) (A), water supply (B), level control pit (C), groundwater level (D), soil moisture content 20 cm-ss (E), 40 cm-ss (F), and 60 cm-ss (G), drainage and infiltration of the ditch (H) and of the pipes (I), and upward and downward seepage (J).

3.7.3.4 Field site D

a) Field site D – calibration

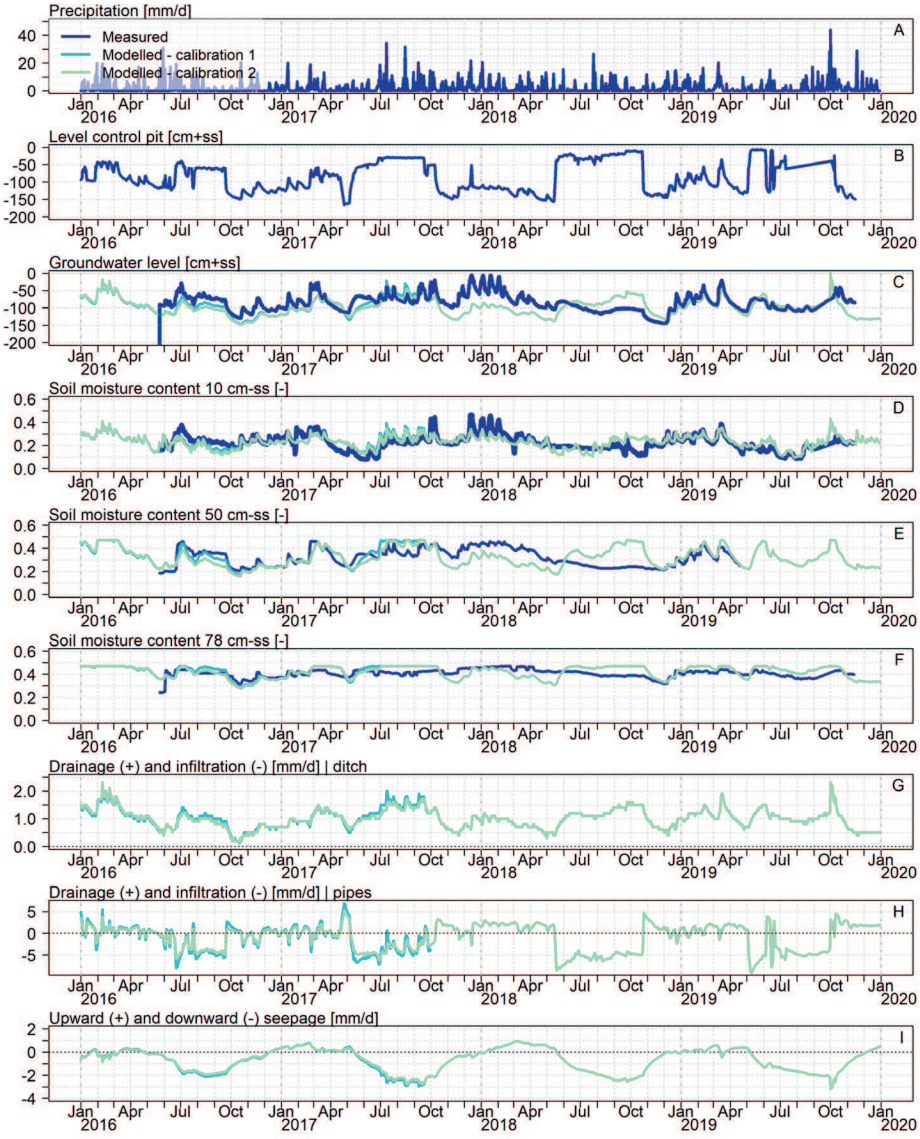


Figure 3.24: Field scale calibration SWAP with PEST with the goal to optimize the soil- and hydrologic parameters for the SWAP model for field site D. Calibration is based on the measurements: groundwater level and soil moisture at 10 cm, 50, and 78 cm-ss. Measured precipitation at KNMI station Twenthe (number 290) (input) (A), level control pit (input) (B), groundwater level (C), soil moisture content 10 cm-ss (D), 50 cm-ss (E), and 78 cm-ss (F), drainage and infiltration of the ditch (G) and of the pipes (H), and upward and downward seepage (I).

Remark: the modelled groundwater levels in year 2018 deviate from the measurements. The modelled groundwater levels in winter 2017-2018 are lower than the modelled groundwater levels in summer 2018, probably due to clogging. The measured groundwater levels show the opposite trend.

*b) Field site D – validation (see *.swp and *.dra file in supplementary material)*

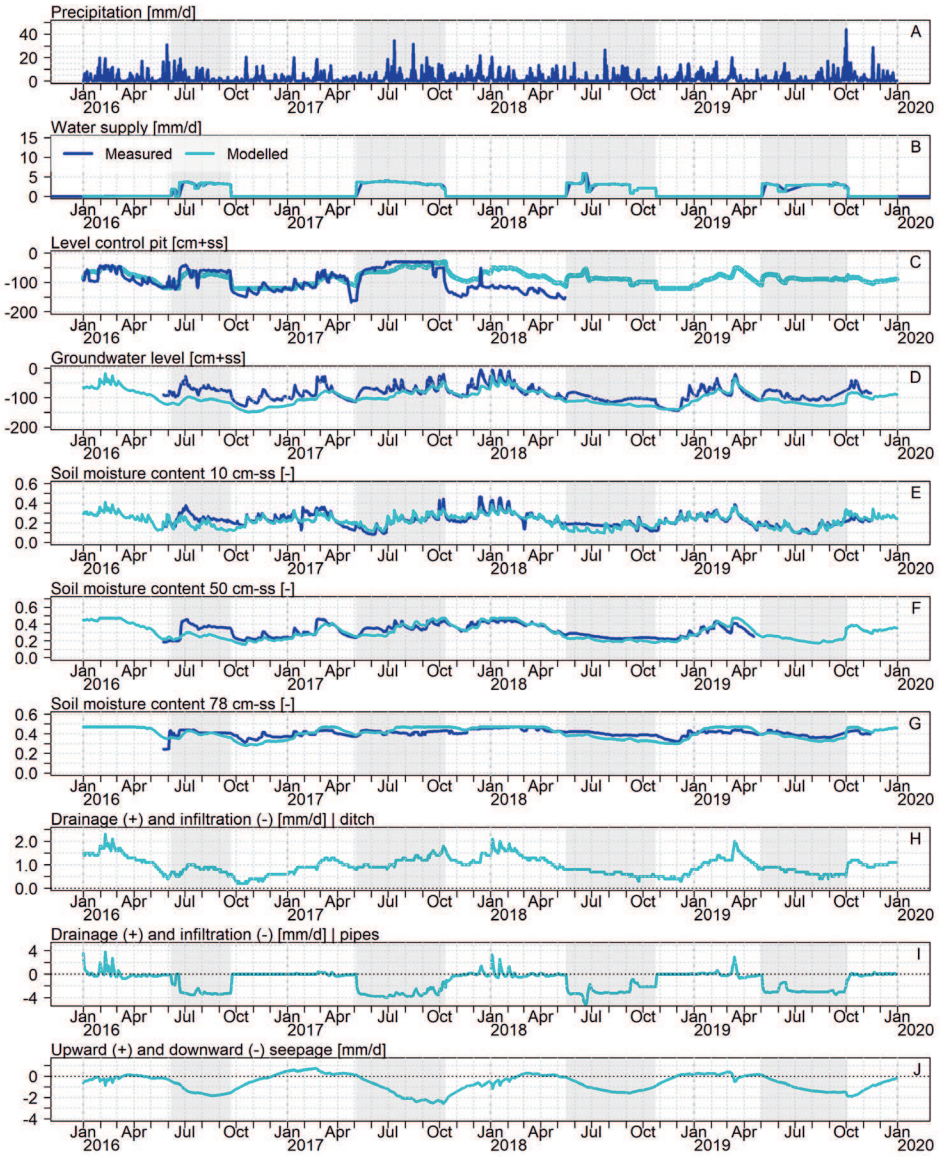


Figure 3.25: Validation with the calibrated SWAP model for field site D (2016-2020). Measured precipitation at KNMI station Twenthe (number 290) (input) (A), water supply (B), level control pit (C), groundwater level (D), soil moisture content 10 cm-ss (E), 58 cm-ss (F), and 78 cm-ss (G), drainage and infiltration of the ditch (H) and of the pipes (I), and upward and downward seepage (J). The grey blocks represent the period of water supply.

c) Field site D – application

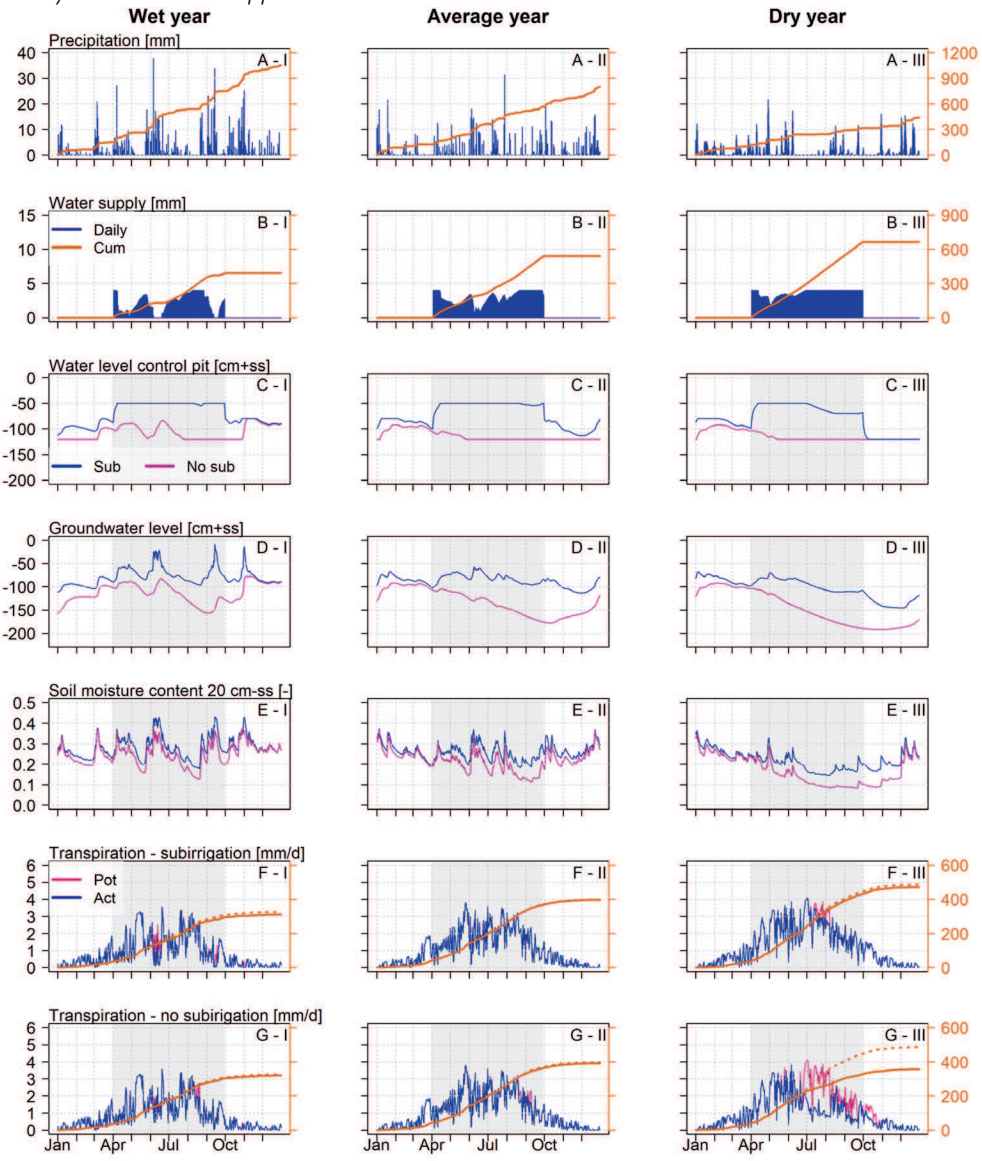


Figure 3.26: Hydrological consequences of controlled drainage with subirrigation for a wet year 1998 (I, left side), an average year 2012 (II, middle) and a dry year 2018 (III, right side), as modelled with SWAP for field site D. Precipitation (input, A), water supply (modelled, B), water level in the control pit (modelled, C), groundwater level (modelled, D), soil moisture content at 20 cm-ss (modelled, E), and potential and actual transpiration (modelled, F). Precipitation and water supply are given in daily ('Daily') base cumulative ('cum') amounts. Water level in the control pit, groundwater level, and soil moisture content at 20 cm-ss are given for a situation without subirrigation ('no sub') and with subirrigation ('sub'). The grey blocks represent the subirrigation period (1st April – 30th September).

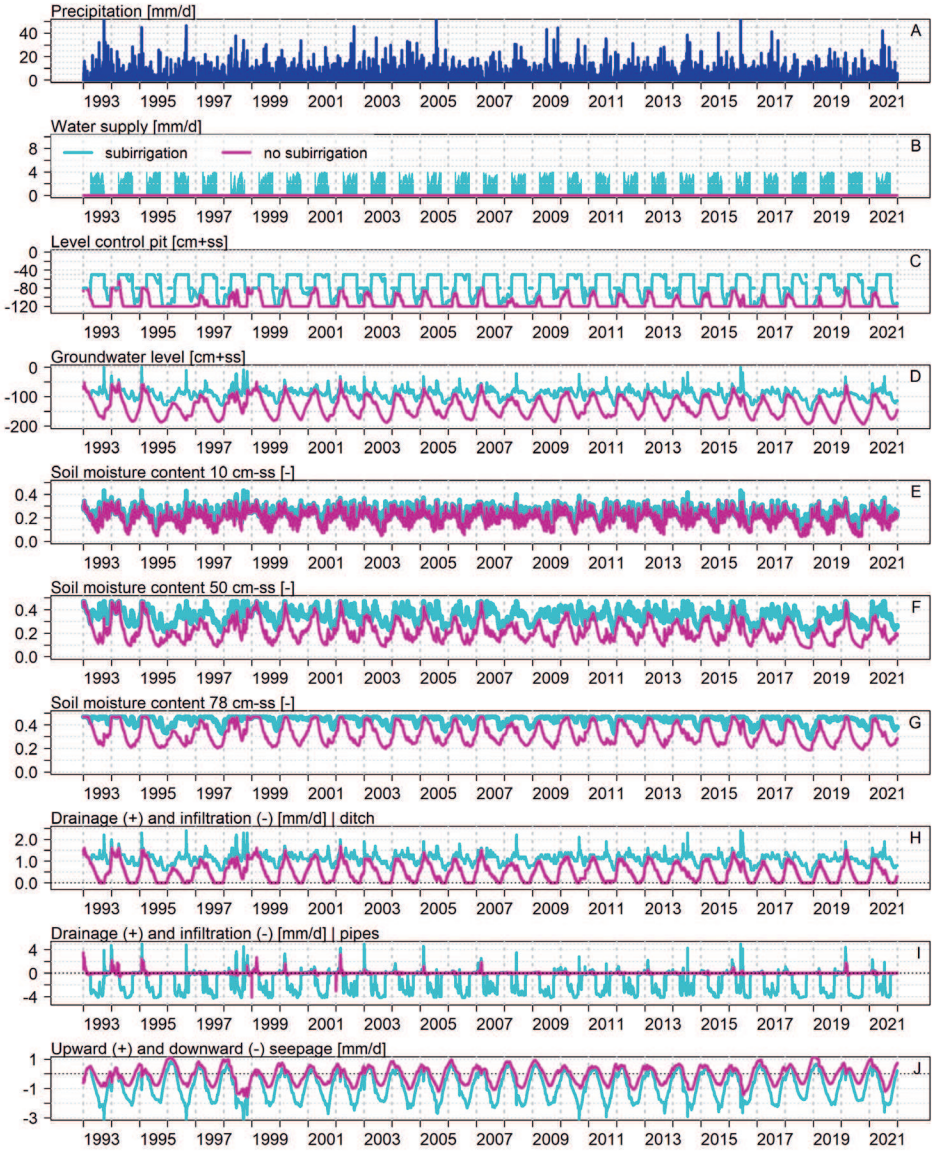


Figure 3.27: Application with the calibrated SWAP model for field site D. Measured precipitation at KNMI station Arcen (number 391) (input) (A), water supply (B), level control pit (C), groundwater level (D), soil moisture content 10 cm-ss (E), 50 cm-ss (F), and 78 cm-ss (G), drainage and infiltration of the ditch (H) and of the pipes (I), and upward and downward seepage (J).

3.7.3.5 Statistics calibration (two steps) and validation

Table 3.4: Coefficient of variation for the calibrated parameters with PEST for the SWAP models of site A, B, C, D.

Parameter calibration	Site A	Site B	Site C	Site D
aqavep	0.126	0.018	0.042	0.050
k0p1	0.001	0.002	0.000	0.001
k0p2	0.003	0.003	0.005	0.007
alfap1	0.038	0.017	0.093	0.049
alfap2	0.025	0.028	0.039	0.046
nparp1	0.007	0.005	0.014	0.008
nparp2	0.014	0.010	0.013	0.010
rdrainp1	0.110	0.059	0.105	0.054
rdrainp2	0.025	0.023	0.028	0.031
rimlayp	0.065	0.020	0.048	0.047
rdrainp1.cal2	0.096	0.069	0.078	0.054
rdrainp2.cal2	0.045	0.015	0.027	0.017
rimlayp.cal2	0.064	0.022	0.052	0.038

4

CHAPTER 4

CONTROLLED DRAINAGE WITH SUBIRRIGATION SYSTEMS: REDUCE WATER SUPPLY BY AUTOMATIC CONTROL

This chapter is based on the publication:
De Wit J.A., van Dam J.C., van den Eertwegh G.A.P.H., van Huijgevoort M.H.J., Ritsema C.J., Bartholomeus R.P. (2024) Controlled drainage with subirrigation systems: Reduce water supply by automatic control. Agricultural Water Management 303:109022. DOI: https://doi.org/10.1016/j.agwat.2024.109022.

Highlights

- Controlled drainage with subirrigation could supply, retain and discharge water.
- Dynamic CDSI control reduces the water supply, while maintaining crop yield.
- Accepting minor water stress may result in significant reductions in water supply.
- Environmental and crop characteristics determine the total water supply.

Abstract

Controlled drainage with subirrigation (CDSI) is a viable measure to supply, retain or discharge groundwater, thereby contributing to freshwater availability in agriculture under changing environmental conditions. Relatively simple CDSI systems can be controlled manually to set a few drainage levels. More advanced systems can be controlled remotely to set any drainage level (between a technical maximum and minimum). CDSI potentially improves hydrological conditions for crop growth, but the required external water supply can be large. Therefore, the objective of this chapter is to investigate whether external water supply for subirrigation can be reduced by automatic control of CDSI systems in relation to crop water demand. Field measurements of a CDSI pilot in the Dutch sandy Pleistocene uplands were combined with weather forecasts to simulate the optimal drainage level and day by day water demand and supply using the agro-hydrological Soil, Water, Atmosphere, Plant model (SWAP). Firstly, model simulations showed that the water requirement reduced by 60 mm (dry growing season), 253 mm (average growing season) and 348 mm (wet growing season) using a dynamically managed crest level (CDSI-dyn) compared to using a fixed crest level (CDSI-fix), with minor effects on crop yield. Secondly, model simulations showed that a higher hydraulic resistance to downward seepage, a higher ditch water level or deeper roots reduced the water supply (up to 100 mm). Thirdly, accepting 10% daily crop drought and oxygen stress for CDSI-dyn reduced the water supply requirement with 235 to 628 mm (dry vs wet growing season) compared to CDSI-fix. In conclusion, the required water volume for CDSI could be substantially reduced by automated control of the drainage level and water supply rate, while maintaining crop yield or accepting minor reductions, which increases the potential of implementation of CDSI systems.

Keywords

Tile drainage, drought, freshwater availability, SWAP, water management

4.1 Introduction

Climate change, weather extremes, economic growth, urbanization, land subsidence and increased food production, among other things, are making it increasingly difficult to guarantee sufficient fresh water in agricultural and economic sectors. Particularly the weather extremes are causing extremely dry to extremely wet conditions (Philip et al., 2020; Teuling, 2018). One possible way to redress the imbalance in the agricultural sector is to use controlled drainage with subirrigation (CDSI) systems, which could be a viable measure to i) retain, ii) recharge, and iii) discharge fresh water.

In the Netherlands, tile drainage systems (the rest of this chapter refers to this as drainage systems) have been developed continuously since they were widely installed from 1950 onwards (De Wit et al., 2022; Stuyt, 2013). The water strategy in the Netherlands shifted from discharge, to discharge + retention, to discharge + retention + recharge (Ritzema and Stuyt, 2015). In the past, drainage systems were mainly installed to remove water in wet periods, called conventional drainage. These pipe drainage systems have been installed on approximately 34% of the Dutch agricultural fields (Massop and Schuiling, 2016). Later, some of these drainage systems were converted to controlled drainage (CD) systems in order to also retain water by reducing drainage (Ayars et al., 2006; Skaggs et al., 2012a). Nowadays, water can also be pumped into these controlled drainage systems ('subirrigation') to recharge groundwater and decrease crop stress (De Wit et al., 2022; Singh et al., 2022).

A CDSI system contains drainage pipes consisting of single drains connected by one closed collector pipe at the end of the field (Figure 4.1). The collector pipe is connected with a control pit and the control pit is connected with an adjacent ditch. The crest level (H_{crest}) in the control pit can be set online or manually. The set H_{crest} results in a drainage base (WL_{pit}) for the corresponding agricultural field. The drainage base regulates the groundwater level. Depending on both soil physical conditions determining capillary rise and crop rooting depth, CDSI systems could increase crop water availability and crop yield (Ng et al., 2002).

CDSI systems improve hydrological conditions for crop growth, but the required water volume can be large (ranging between roughly 500 to 1000 mm) (De Wit et al., 2024c; Jouni et al., 2018), which is mainly caused by the applied drainage and pumping strategy. The crest level is generally controlled manually which only allows a few drainage levels. In practice, this means that the crest level is set to the maximum height during a certain time, for example (part of) the growing season (1st April – 30th September). Doing so, water is often applied continuously to ensure that the control pit is always filled with water to the crest level. Therefore, this strategy focusses on maintaining a specific (fixed) groundwater level (Mejia et al., 2000; Wesström et al., 2014). However, this strategy does not take into

account the actual crop needs during the growing season determined by variations in plant water demand and meteorological conditions.

More advanced CDSI systems, like Climate Adaptive Drainage (Van den Eertwegh et al., 2013), can be controlled remotely, and can be set to any drainage level (between a technical maximum and minimum). By combining the remote control with a modelling procedure, these systems function as so called dynamically controlled CDSI systems. Doing so, the crest level and amount of water supply (W_{supply}) can be set daily according to a combination of the current field conditions, the weather forecast and crop water requirements. As water supply is automatically tailored to the actual water need for subirrigation in relation to plant water demand, the automatic pumping strategy could result in lower water supply compared to manual management. Therefore, the research question addressed in this study was: To what extent is it possible to reduce external water supply for subirrigation by automatic control of CDSI systems in relation to crop water demand?

To control CDSI systems dynamically, we used a process-based field scale hydrological model of an experimental site in the Dutch Pleistocene uplands where CDSI is applied. In this study, we combined a calibrated model with the actual soil moisture conditions and the weather forecast to calculate an optimal drainage level and amount of water supply (Figure 4.1). Additionally, we investigated the required water supply and hydrological effects of CDSI for subtle differences in geohydrological characteristics and variations in crop rooting depth (further defined in the method section). Finally, we compared the hydrological effects of four types of drainage systems (conventional drainage, controlled drainage, CDSI fixed and CDSI dynamic). All simulations were focussed on a relatively wet, an average and an extremely dry growing season.

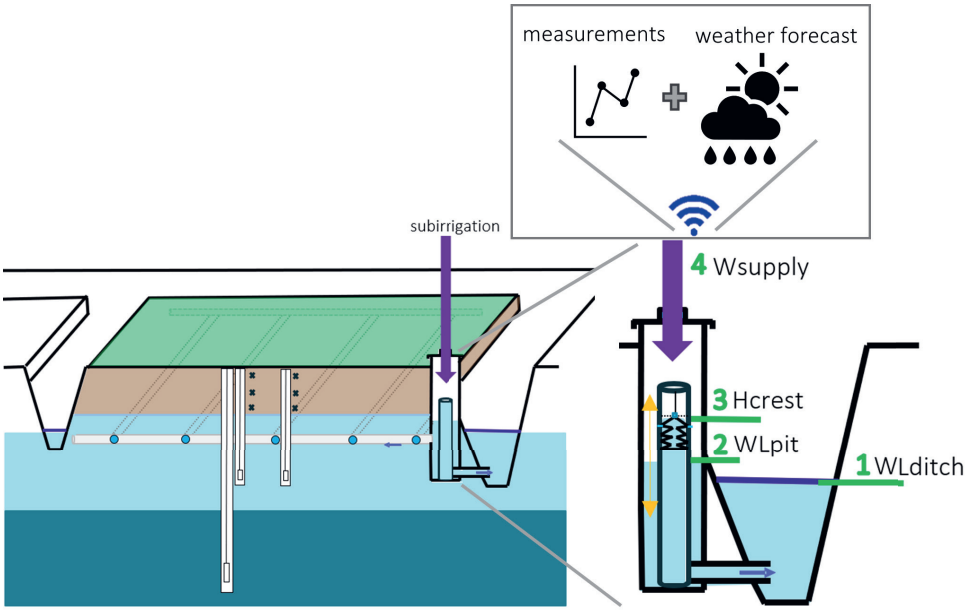


Figure 4.1: Schematization of an automatically controlled drainage system with subirrigation. The drainage pipes are represented in grey. The ditch water level (1, 'WL_{ditch}'), pit water level or drainage base (2, 'WL_{pit}'), height of the fixed or online controlled weir in the pit (3, 'H_{crest}'), and the water supply (4, 'W_{supply}') are indicated. Optimal H_{crest} can be estimated using field measurements, the weather forecast and a modelling algorithm. Field measurements are: shallow and deep hydraulic head, soil moisture content at 20, 40, 60 cm depth, soil water potential at 20, 40, 60 cm depth, WL_{ditch}, WL_{pit}, H_{crest} and W_{supply}. Figure adapted from De Wit et al. (2024c).

4.2 Methods

4.2.1 Experimental site

We focus on an experimental site located in the southeast of the Dutch sandy Pleistocene uplands (town America; 51º27'N, 5º57'E) where CDSI was applied (Figure 4.2-I). The set up of the CDSI system was a control pit where water was pumped in (source is groundwater) or water was drained to the adjacent ditch. The control pit was connected with a collector drain parallel to the ditch (Figure 4.2-II). The 12 drainage pipes (each approximately 400 m long and the pipes were about level) were placed perpendicular to the collector drain, at roughly 1.20 meter below soil surface (m-ss) with 6 m spacing. Two shallow piezometers were installed near and between two drains to measure the phreatic groundwater level, one piezometer was installed between two drains to measure the deep hydraulic head (Figure 4.1). The crops were (perennial rye) grass (2017-2019, 2021-2022) and carrots (2020). The phreatic groundwater levels varied between 90-180 centimeters below soil surface (cm-ss). The ditch level varied between 150 cm-ss (summer) and 160 cm-ss (winter), both levels were determined and set by the regional water board. Furthermore, the experimental site contains a sandy soil with a resistant (lower hydraulic conductivity) loam layer in the subsoil (2.0 – 2.5 m-ss) based on the field soil profile description. Based on

this description, the soil properties were specified according to Heinen et al. (2020). After that, the soil hydraulic parameters of the first two soil layers (saturated vertical hydraulic conductivity, shape parameter alfa of the main drying curve, shape parameter n of Van Genuchten (1980)) were calibrated, as described in De Wit et al. (2024c). The details of the parameters for these soil layers are described in Table 4.1 and are included in the *.swp file in the online supplementary material. The field surface area is 3.77 ha with an average field height of 30.72 meter above mean sea level (m+MSL). A reference field with similar equipment but no subirrigation was located adjacent to the subirrigation field.

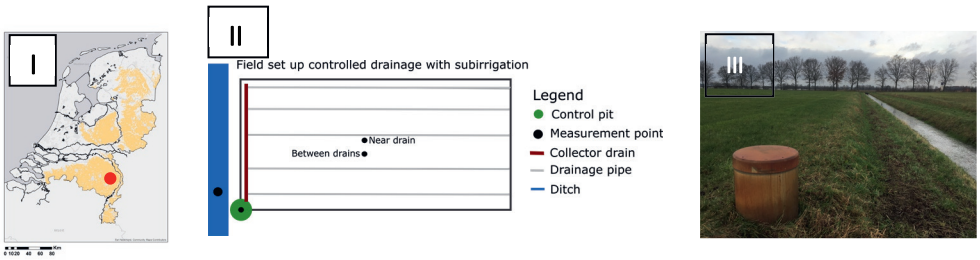


Figure 4.2: The Netherlands with the (drought sensitive) sandy Pleistocene uplands in yellow (I) (0 – 100 m+MSL). The red dot represents the location of the field experiment. II: schematic field setup of CDSI. III: a picture of the control pit at the experimental field site.

The field measurements are schematized in Figure 4.1. W_{supply} was measured daily with the ZENNER PN16 - Qn 6 BH (2017-2020) and a KAMSTRUP flowIQ® 3100 meter (2021-2022). WL_{pit} was measured every 15 minutes with the KELLER DCX-22. WL_{pit}, the *GWL* and the hydraulic head were measured every 15 minutes with a CTD-10 sensor (METER). H_{crest} was in practice almost always at 50 cm-ss. *SMC* and *SWP* at 20 cm-ss, 40 cm-ss and 60 cm-ss were measured every 15 minutes with respectively the 5TE sensor and TEROS-21 sensor. All further details are described in De Wit et al. (2023b).

Table 4.1: The soil hydraulic parameters for four soil layers used in the soil schematization of the SWAP model. Soil hydraulic parameters are, according to Van Genuchten (1980): residual water content (ORES), saturated water content (OSAT), shape parameter alfa of main drying curve (ALFA), shape parameter n (NPAR), saturated vertical hydraulic conductivity (KSAT), exponent in hydraulic conductivity function (LEXP). The parameterization is based on the schematization of the soil profile made at the field site and calibration of the parameters OSAT, KSAT, ALFA and NPAR according to De Wit et al. (2024c).

Soil layer and depth	Soil depth	ORES	OSAT	ALFA	NPAR	KSAT	LEXP
[-]	cm	cm^3/cm^3	cm^3/cm^3	cm^{-1}	[-]	cm/d	[-]
1	0 – 30	0.02	0.43	0.04	1.36	30.83	0.00
2	30 – 200	0.01	0.36	0.02	1.72	5.00	0.00
3	200 – 220	0.01	0.38	0.003	1.728	1.51	-0.292
4	220 – 500	0.01	0.36	0.0224	1.801	15.22	0.00

4.2.2 Field scale modelling

4.2.2.1 Field scale model SWAP

The agro-hydrological 1D-model Soil, Water, Atmosphere and Plant (SWAP) has been developed over a period of 50 years to simulate the transport of water, solutes and heat in the vadose zone, in interaction with crop growth (Heinen et al., 2024; Kroes et al., 2017). In case of drainage simulations, the most important input parameters are the meteorological conditions, soil hydraulic parameters (Van Genuchten, 1980), hydraulic head in the underlaying aquifer, hydraulic resistance to downward seepage, crop rooting depth, critical soil water pressure heads for root water uptake, and lateral drainage (whose parameters are explained in the following section). SWAP calculates, among other things, the hydrological fluxes (interception, evaporation, transpiration, seepage, infiltration and drainage), *GWL*, *SMC* and crop stress. Crop drought and oxygen stresses were estimated in terms of transpiration reduction (potential transpiration – actual transpiration) due to limited moisture or oxygen availability in the root zone (Heinen et al., 2024).

Drainage can be simulated via i) the basic drainage option when surface water levels are fixed and ii) via the extended drainage option to calculate dynamic water levels. The extended drainage is used in this study, following De Wit et al. (2024c). The 'first order drainage system' is used to simulate ditch drainage and infiltration for which ditch water levels (WL_{ditch}, Figure 4.1) are input. The 'secondary drainage system' is used to simulate controlled drainage with subirrigation.

4.2.2.2 SWAP modelling for four drainage systems

One general SWAP model was set up in this study based on the schematization of Figure 4.1 and the field site A described in De Wit et al. (2024c). Meteorological conditions of the nearest weather station (KNMI nr. 391, Arcen) were used as input (parameters: temperature (minimum, maximum), precipitation (intensity and duration) and reference transpiration according to Makkink (1957)). Crop input for all years was grass with a rooting depth of 30 cm-ss. The grass file represents the characteristics of perennial ryegrass (Kroes and Supit, 2011). The bottom flux (upward (+) or downward (-) seepage) was estimated based on the interaction between i) the groundwater level, ii) the hydraulic head in the deep aquifer and iii) the hydraulic resistance to downward seepage. The hydraulic head in the deep aquifer was defined as a sine function (average hydraulic head of 202 cm-ss, amplitude of 60 cm, period of 365 days and highest value at day 30 of the year). In SWAP, the resistance to downward seepage in days ('d') reflects the regional geohydrological and drainage system (Bartholomeus et al., 2019; Kroes et al., 2017; Van der Gaast, 2006) and was obtained by calibration (800 d (De Wit et al., 2024c)). The ditch drainage resistance determines the drainage to the ditch (defined as lateral drainage) and was calibrated on 350 d (De Wit et al., 2024c). Ditch level was 150 cm-ss. Input files *.swp, *.dra and GrassS.crp are provided as online supplementary Material. Output (per day) is, among

other things, the actual water supply for subirrigation, WL_{pit}, GWL, water balance components and crop water stress (drought and oxygen stress).

We distinguished four drainage systems: conventional drainage (conv), controlled drainage (CD), CDSI with a fixed crest level and fixed water supply rate (CDSI-fix) and CDSI with a dynamic crest and dynamic water supply control (CDSI-dyn). The depth and spacing of the drainage pipes were similar for all systems: 120 cm-ss and 6 m respectively. These four drainage systems were set up in four SWAP simulations, using the general SWAP model set up. The following characteristics were changed in the general SWAP model (Figure 4.3): i) Conventional drainage aims to discharge water; yearly H_{crest} = 120 cm-ss (equal to drain depth), ii) Controlled drainage aims to both retain and discharge water; H_{crest} = 50 cm-ss (year-round), based on field experiments (De Wit et al., 2024c), iii) CDSI-fixed aims to retain, recharge, and discharge water. H_{crest} was set to 50 cm-ss throughout the year and maximal water supply was set to 5 mm/d in the growing season (1st April – 30th September), based on field experiments (De Wit et al., 2024c). Both the daily water supply and the daily water level in the control pit of the CDSI system were simulated dynamically, which is a key element in understanding the functioning of CDSI systems (De Wit et al., 2024c), and iv) CDSI-dyn aims to automatically determine when and how much water to retain, recharge and discharge, considering the actual field conditions, crop water demand and weather forecasts, further explained in section 4.2.2.3.

All four drainage systems were simulated for 10 years (2013 - 2022), in the analysis we focused on a relatively wet (2014), an average (2016) and an extremely dry (2018) year. These years were defined based on precipitation surplus in the growing season. Precipitation in the growing season was 477, 420, and 198 mm for 2014, 2016, 2018 respectively. Precipitation over the total year was 747, 793, and 445 mm for 2014, 2016, 2018 respectively. Reference crop evapotranspiration (ET_{ref}, according Makkink (1957)) in the growing season was 475, 506, and 578 mm for 2014, 2016, 2018 respectively. Thus, in the growing season there was a precipitation surplus (P - ET_{ref}) of 2, -86 and -380 mm for 2014, 2016, 2018 respectively.

We simulated all four drainage systems using the same general drainage concept in SWAP in order to make a good comparison between the types of drainage. These simulations aimed to investigate the impact of different drainage systems on crop water availability, water balance components and, for CDSI, crest level and amount of water supply.

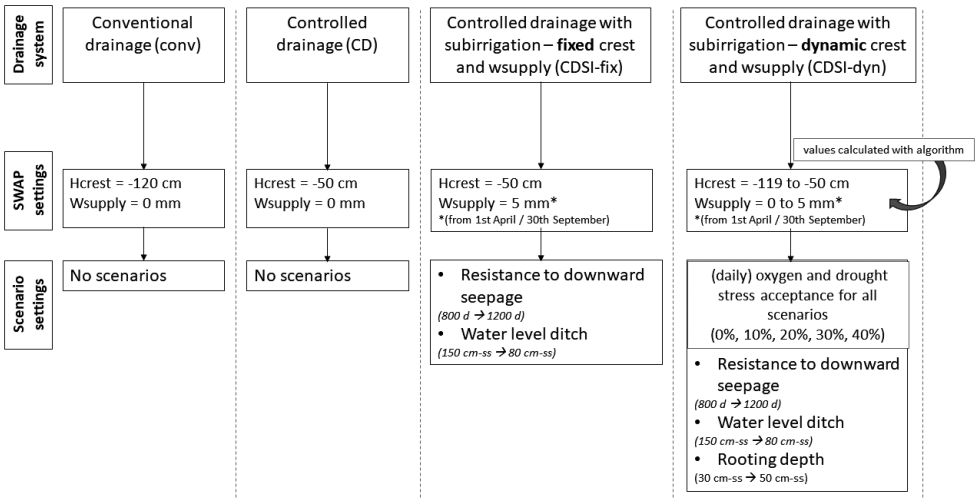


Figure 4.3: Overview of all simulations with the field scale model SWAP. In total, four drainage systems (conventional drainage, controlled drainage, CDSI fixed and CDSI dynamic) were simulated for 10 years (2013 - 2022). CDSI (fixed and dynamic) were simulated with subtle differences in geohydrological characteristics (resistance to downward seepage and water level ditch). CDSI dynamic was also simulated with differences in rooting depth and stress (oxygen and drought stress) acceptance.

4.2.2.3 *Automatic control CDSI systems*

To control CDSI systems automatically, we aimed to simulate the optimal crest level and water supply amount for the current day, to reduce water supply at field scale in relation to crop water demand. In order to calculate the optimal crest level and amount of water supply, we followed two steps: forecast and optimization.

The forecast step aims to forecast the hydrological conditions and plant stress for the next 10 days. Input for the forecast step is the output of the calibrated SWAP model (section 4.2.2.2) and the weather forecast of KNMI station Arcen. Output state variables are daily drainage level, groundwater level, soil moisture content, drainage flux, and plant oxygen and drought stress.

The optimization step aims to simulate the optimal crest level and amount of water supply for the current day, to reduce water supply at field scale while maintaining crop water availability. In order to do so, input for the optimization step is the output of the forecast step. The forecasted oxygen and drought stress and the drainage flux are weighted using a sigmoid function, i.e. output in the near future gets more weight than output in the further future. The sum of the weighted output is compared with acceptable oxygen and drought stress (in percentage, set by the user), and drainage (0.001 cm/d). A new crest level or adjusted amount of water supply is recommended depending on whether there is:

1. Oxygen stress (option 1): lower crest level to discharge water;
2. Unnecessary drainage (option 2): raise crest level to retain water;
3. Drought stress (option 3): maximum crest level and supply water;
4. No oxygen and drought stress and no drainage (option 4): no action, keep crest level.

Based on the option chosen, the new crest level ranges between the deepest (option 1) or shallowest (option 2) drainage level, if needed combined with water supply (option 3). If a new crest level is recommended, then also a new weighted stress or drainage is calculated. After that, this process is iteratively repeated until the optimal combination of crest level and water supply is calculated with acceptable oxygen stress (option 1), minimal drainage (option 2) and acceptable drought stress (option 3).

4.2.2.4 CDSI scenarios

CDSI (fixed and dynamic) systems were also simulated with subtle differences in geohydrological characteristics and crop rooting depth (Figure 4.3). Geohydrological characteristics were defined as i) increasing the hydraulic resistance to downward seepage from 800 d to 1200 d (first scenario for CDSI-fix and CDSI-dyn) and ii) raising the ditch level from 150 cm-ss to 80 cm-ss (second scenario for CDSI-fix and CDSI-dyn). Since the hydraulic resistance to downward seepage occurred as a result of the regional geohydrological system (section 4.2.2.2), it is a characteristic of a certain region that is unchangeable on field scale. However, changing the value for the model runs, provides insight in the effects of CDSI in an area with different regional characteristics. Second, the ditch level is a changeable characteristic set by the water board (section 4.2.1). CDSI systems result in a higher groundwater level such that the head difference between the groundwater level and ditch level increases, increasing drainage losses. The scenario of raising ditch levels thus provides insight in reduced drainage losses and the consequences for water supply and other water balance components when implementing CDSI-systems. Third, CDSI-dyn was also simulated with a crop rooting depth of 50 cm instead of 30 cm (third scenario for CDSI-dyn). All three scenarios of CDSI-dyn were simulated with differences in acceptance of crop water stress in the automated control: the effect of daily acceptance of oxygen and drought stress of 0%, 10%, 20%, 30% and 40% was analysed. All scenario simulations (2 for CDSI-fix, 15 for CDSI-dyn) aimed to investigate how geohydrological characteristics, crop rooting depth and acceptance of crop water stress impact the amount of water supply in relation with crop water availability and how they impact water balance components.

4.3 Results

4.3.1 Hydrological consequences of different drainage systems

The four drainage systems affected the hydrological fluxes differently. First, conventional drainage aims to discharge water with a crest level of 120 cm-ss (Figure 4.3, Figure 4.4C), and a corresponding pit water level of approximately 120 cm-ss (Figure 4.4D). A low pit level resulted in a groundwater level fluctuating between 100 cm-ss and 250 cm-ss (Figure 4.4E) with the consequence of high cumulative yearly drought stress, especially in the drier years 2018, 2020, 2022 (Figure 4.4G), and yearly cumulative oxygen stress between 0 and 4 mm (i.e. negligible) (Figure 4.4H). Lateral ditch drainage was maximal 1 mm/d because the groundwater level was generally lower than the surface water level (Figure 4.4I). Therefore, water mainly exited the system as downward seepage ranging from 0 to 1.5 mm/d (Figure 4.4K).

Second, controlled drainage aims to retain water, and only discharge water if really needed. Due to the fixed crest level of 50 cm-ss, the pit level fluctuated between 50 – 120 cm-ss as precipitation was retained (Figure 4.4D). A higher pit level also resulted in a slight increase in groundwater level in wintertime compared to conventional drainage (Figure 4.4E). The retention of water slightly reduced drought stress in the dry year 2020 (200 mm/y) compared to conventional drainage (220 mm/y) (Figure 4.4G). However, a continuous high crest level also slightly (but negligible) increased oxygen stress in the wet year 2016 (4 mm/y) compared to conventional drainage (3.5 mm/y) (Figure 4.4H).

Third, controlled drainage with subirrigation with a fixed crest aims to retain and recharge water, and only discharge water if really needed. For this study, this means a water supply in the growing season of 5 mm/d (Figure 4.4B) and a fixed crest level of 50 cm-ss (Figure 4.4C). A high crest level resulted in a fluctuating pit water level between 50 cm-ss and 120 cm-ss (Figure 4.4D). As a result, the groundwater level ranged between 30 cm-ss and 120 cm-ss (Figure 4.4E) and drought stress ranged between 0 to 50 mm/y (Figure 4.4G). Oxygen stress was negligible (up to 1 mm/y) (Figure 4.4H). Due to continuous water supply and larger head differences, more water exited the system as ditch drainage and downward seepage compared to CD systems (Figure 4.4I – K). Thus, CDSI-fix resulted in high water supply (800 – 1000 mm/y), high pit water level and groundwater level and minimum drought stress while hardly leading to oxygen stress. However, ditch drainage and downward seepage were relatively high.

Fourth, controlled drainage with subirrigation with a dynamic crest level and water supply (and daily acceptance of 10% oxygen and drought stress) also aims to retain and recharge water, and only discharge water if really needed. Due to the dynamic crest level, water supply reduced compared to CDSI-fix (Figure 4.4H) (180 – 800 mm/y vs 800 – 1000 mm/y).

Therefore, pit water level and groundwater level were both lower than for CDSI-fix. Pit level and groundwater level ranged between 50 – 120 cm-ss and 50 – 160 cm-ss respectively. Drought stress was circa 20 mm/y in wetter years, circa 50 mm/y in average years, and 50 – 100 mm/y in drier years (Figure 4.4G), including acceptance of 10% daily drought stress. Oxygen stress was up to 0.5 mm/y (Figure 4.4H). Thus, CDSI-dyn resulted in less water supply (100 – 600 mm/y), lower pit level and groundwater level, a bit more drought stress, less oxygen stress, and less ditch drainage and downward seepage compared to CDSI-fix systems.

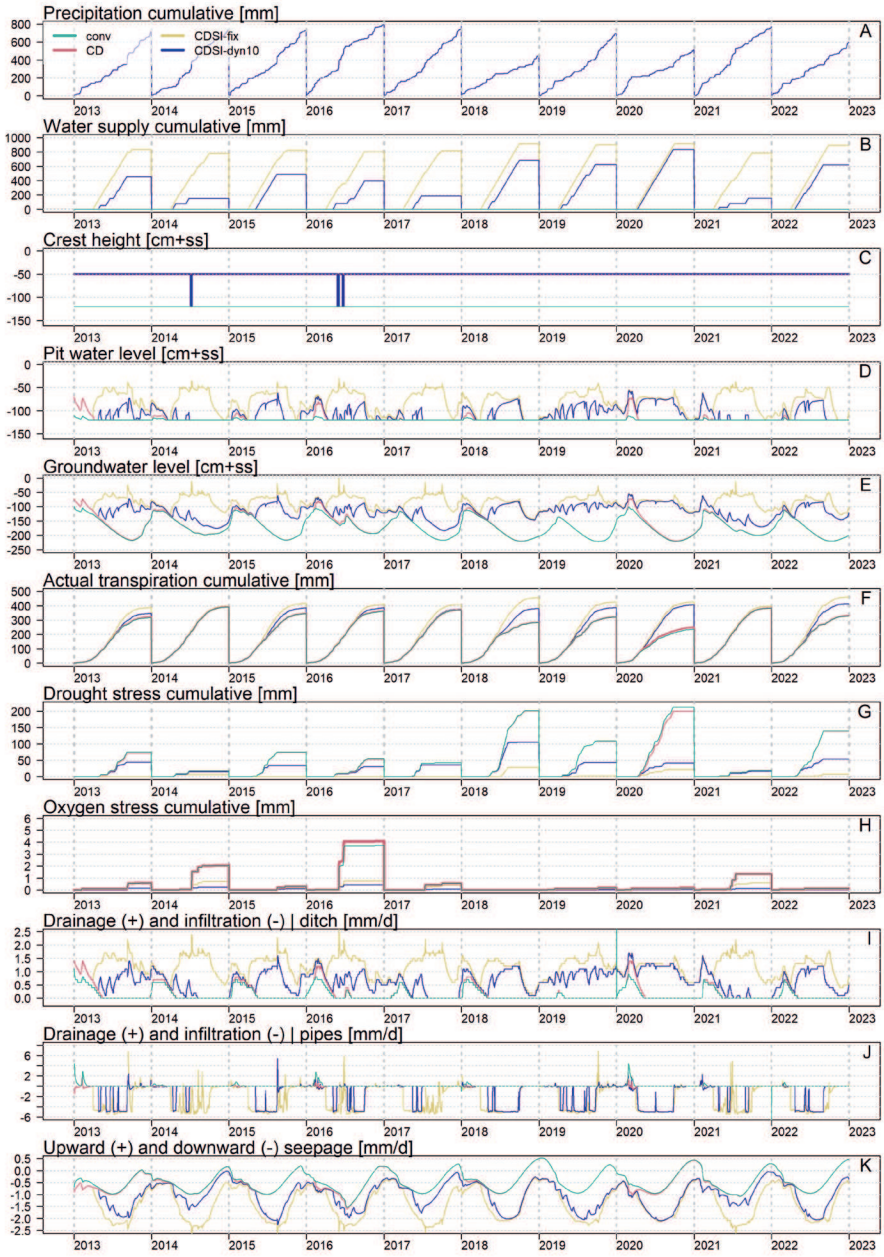


Figure 4.4: Overview of measured cumulative precipitation of the KNMI station Arcen (A), cumulative water supply (B), crest height (C), pit water level (D), groundwater level (E), cumulative actual transpiration (F), cumulative drought stress (G), cumulative oxygen stress (H, please note the difference in scale of the y-axis compared to drought stress), drainage and infiltration of the ditch (I) and drainage pipes (J), and upward and downward seepage (K). All components are calculated with the drainage systems conventional situation with a yearly H_{crest} at -120 cm to drain water ('conv'), controlled drainage with a yearly crest level at -50 cm to retain water ('CD'), controlled drainage with subirrigation (CDSI) with a fixed crest level of -50 cm and daily 5 mm water supply in the growing season (1st April – 30th September) ('fix') and CDSI with a dynamic crest level and dynamic water supply with acceptance of 10% oxygen and drought stress ('dyn10%').

Drainage systems affected the main water balance components (Figure 4.5). Figure 4.5 shows the differences based on the growing season, the values given in the following text are based on the differences in the yearly water balance. First, changing from conventional drainage to CD resulted in less ditch drainage (7 – 30 mm, wet vs avg growing season) due to retention of water and more downward seepage (5 vs 22 mm, wet vs avg growing season). Second, changing from CD to CDSI-fix resulted in a higher water demand (778 – 916 mm, wet vs dry growing season), higher transpiration (6 – 48 – 173 mm, wet vs avg vs dry growing season), higher downward seepage (263 – 307 mm, avg vs wet growing season), and higher ditch drainage (317 – 387 mm, dry vs wet growing season). Third, conversion from CDSI-fix to CDSI-dyn10 resulted in a substantially lower water demand (628 – 408 – 235 mm), decrease of transpiration (3 – 26 – 76 mm), decrease of ditch discharge (322 – 188 – 115 mm), and less downward seepage (210 – 107 – 66 mm, all wet vs avg vs dry growing season). This means that the water demand reduces by accepting minor reductions in transpiration in the daily management.

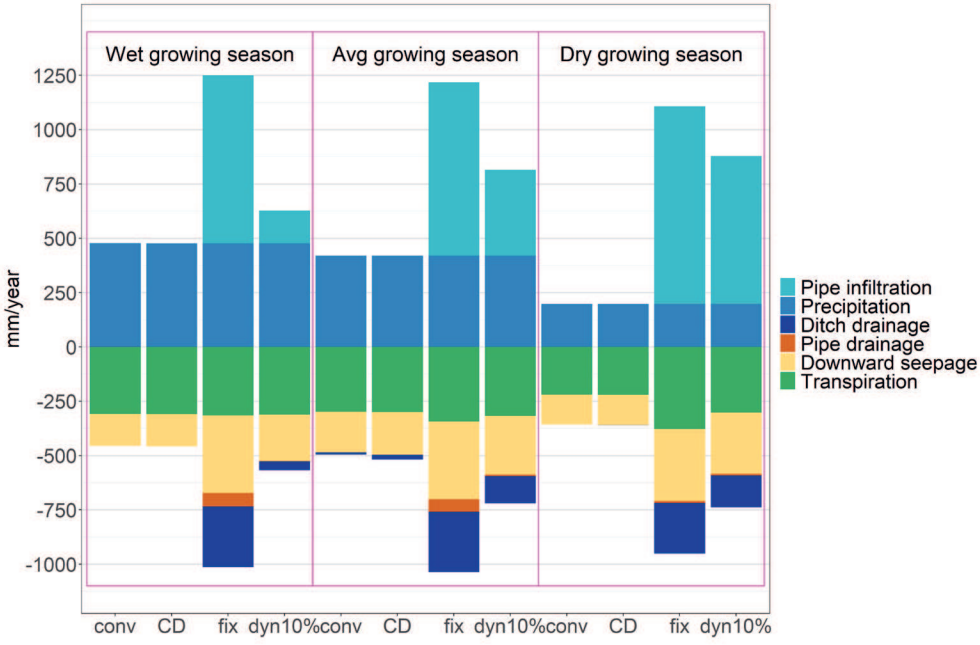


Figure 4.5: Simulated water balance components over the growing season (1st April – 30th September). All components are calculated for a relative wet growing season (2014, 'wet growing season'), an average growing season (2016, 'avg growing season') and an extremely dry growing season (2018, 'dry growing season') for conventional drainage ('conv'), controlled drainage ('CD'), controlled drainage with subirrigation (CDSI) with a fixed crest level and daily 5 mm water supply in the growing season ('fix') and CDSI with a dynamic crest level and dynamic water supply with daily acceptance of 10% oxygen and drought stress ('dyn10%').

Although the absolute distribution of water supply over the water balance components differed per drainage type, the percentual distribution of water supply over the water balance components were similar. All values in the following text are based on differences

between drainage type (CDSI-fix or CDSI-dyn10) compared to CD, since these values indicate the effect of extra water supply in relation to the other water balance components. Please note that the sum of the percentages is not 100% because there were also small changes in other water balance components. In addition, the net effect of subirrigation can be larger than the amount of water supply, for example, due to rainwater retention or changes in (downward) seepage (Figure 4.4). First, for CDSI-fix, W_{supply} of 778 mm is distributed as 6.3 mm to transpiration (1%), 387 mm to ditch drainage (50%), 307 mm to downward seepage (40%) in a wet growing season. In an average growing season, 803 mm water supply is distributed as 48 mm to transpiration (6%), 368 mm to ditch drainage (46%) and 263 mm to downward seepage (33%). In a dry growing season, 916 mm water supply is distributed as 172 mm to transpiration (19%), 317 mm to ditch drainage (35%) and 303 mm to downward seepage (33%). Second, for CDSI-dyn10, 150 mm water supply is distributed as 2.7 mm to transpiration (2%), 65 mm to ditch drainage (43%) and 98 mm to downward seepage (65%) in a wet growing season. In an average growing season, 395 mm water supply is distributed as 22 mm to transpiration (6%), 180 mm to ditch drainage (46%) and 156 mm to downward seepage (39%). In a dry growing season, 681 mm water supply is distributed as 96 mm to transpiration (14%), 202 mm to ditch drainage (30%) and 236 mm to downward seepage (35%). Thus, the distribution of water balance components depends on the type of drainage system. Furthermore, the water supply decreased for CDSI-dyn10 compared to CDSI-fix, but the percentual distribution of water supply over the water balance components in a dry growing season is similar.

4.3.2 Impact of meteorology on hydrological fluxes for different CDSI systems

Water supply differed between CDSI systems with either a fixed or dynamic crest level depending on the eventual precipitation surplus (Figure 4.6). CDSI-fix systems required an almost similar water supply in drier and wetter years (roughly 900 vs 800 mm/y respectively) (Figure 4.6A). The main reason is that in these CDSI-fix systems the control pit is always filled with water to the crest level. This required maximum W_{supply} in both drier and wetter years. In contrast, CDSI-dyn systems required considerably less water supply in eventually wetter years than in drier years (450 vs 850 mm/y) (Figure 4.6B), because the actual needs of the crop during the growing season with all variations in plant water demand and meteorological conditions were taken into account. This required W_{supply} only when plant water requirements could not be met by already available soil moisture (from capillary rise from groundwater and from rainfall). Therefore, differences occurred in water supply between drier and wetter years. In general, CDSI-dyn, managed on a daily basis, eventually resulted in less yearly water supply compared to CDSI-fix (Figure 4.6). This meant that in a relatively wet growing season 45% less water was supplied (430 vs 778 mm, CDSI-dyn vs CDSI-fix), in an average growing season 31% less water was supplied (550 vs 803 mm, CDSI-dyn vs CDSI-fix) and in an extremely dry growing season 6% less water was supplied (855 vs 915 mm, CDSI-dyn vs CDSI-fix).

Water supply of CDSI-fix and CDSI-dyn was comparable in the driest growing seasons 2020 and 2018 (Figure 4.6). Although 2018 is the driest growing season in terms of precipitation surplus, the highest water supply occurred in 2020. A reason might be that 2018 was a 'stand-alone dry' growing season, meaning that the precipitation surplus was high, but water was stored in the soil from a quite wet winter and spring. The growing season 2020 showed a lower cumulative precipitation surplus than 2018, but water supply was higher in 2020 than in 2018. A reason might be that the growing seasons 2018 and 2019 were dry growing seasons, which made 2020 a 'cumulative' dry growing season, for which water storage in the soil was low and thus, required water supply high.

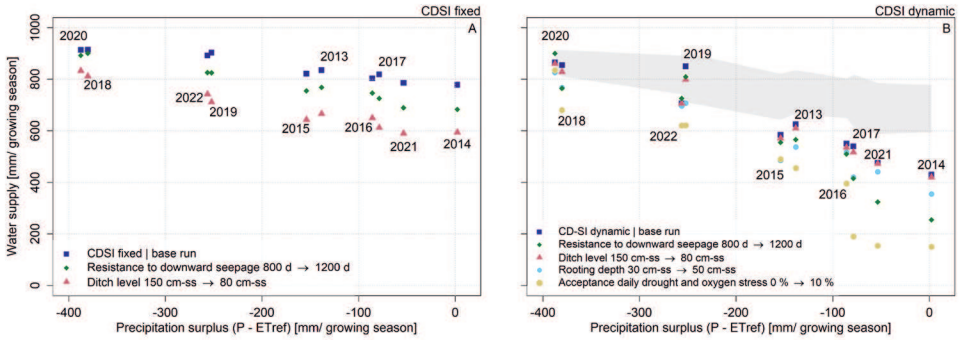


Figure 4.6: The calculated precipitation surplus ($P - ET_{ref}$) in the growing season (1st April – 30th September) versus water supply in the growing season for controlled drainage with subirrigation (CDSI) system using a fixed crest and water supply (A) and using a dynamic crest and water supply (B). Fixed crest level was 50 cm-ss and max. water supply was 5 mm/d in the growing season. Water supply was calculated for the base run, an increased average resistance to downward seepage of 800 d to 1200 d (A and B), a raised ditch level from 150 cm-ss to 80 cm-ss (A and B), an increased rooting depth from 30 cm-ss to 50 cm-ss (B) and acceptance of drought and oxygen stress of 10% (B). The grey area (B) represents the range of values of graph A.

4.3.3 Impact of geohydrological and crop characteristics

4.3.3.1 Changes in water supply of CDSI systems

Geohydrological characteristics impacted the water demand of CDSI systems (Figure 4.6A). Effects were different for a fixed or a dynamic CDSI system. For CDSI-fix this meant (Figure 4.6A) that an increased hydraulic resistance to downward seepage (800 days to 1200 days) resulted in 20 – 150 mm/y less water supply (dry vs wet growing season). Furthermore, a raised ditch level (150 cm-ss to 80 cm-ss) resulted in 200 mm/y less water supply. For CDSI-dyn this meant (Figure 4.6B) that i) an increased hydraulic resistance to downward seepage resulted in 0 – 150 mm/y less water supply, ii) a raised ditch level resulted in 0 – 50 mm/y less water supply, iii) deeper roots (50 cm-ss versus 30 cm-ss) resulted in 150 mm/y less water supply and iv) daily acceptance of 10% drought and oxygen stress (instead of acceptance of 0% drought and oxygen stress) resulted in 200 – 300 mm/y less water supply. Thus, rooting depth and acceptance of drought and oxygen stress reduced water supply most, because CDSI-dyn systems using automatic control actively consider the actual needs of the crop during the growing season.

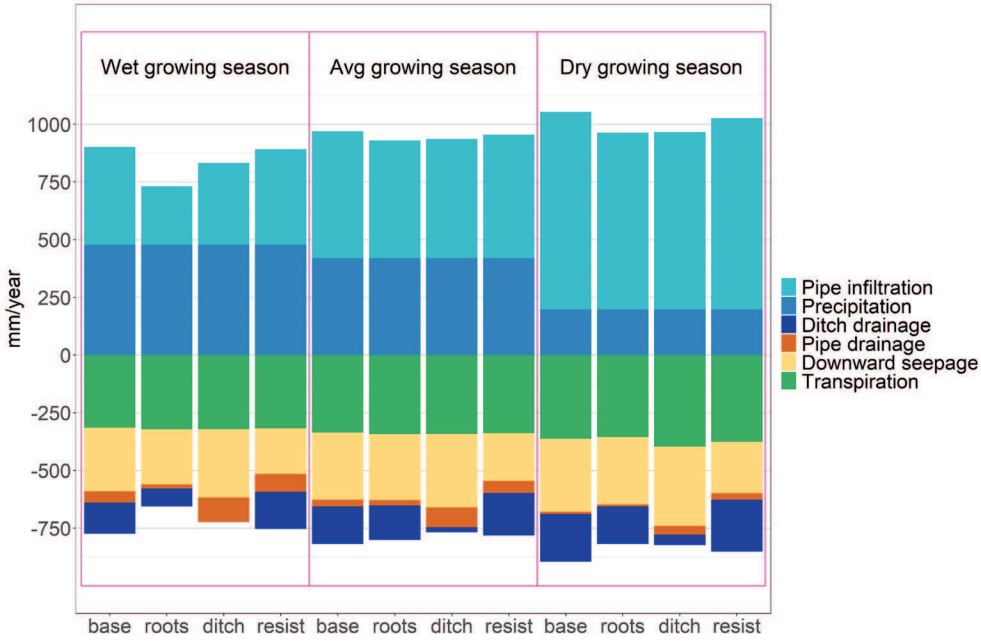


Figure 4.7: Simulated water balance components with the SWAP model, via the algorithm with a dynamic crest level and dynamic water supply. All components were calculated over the growing season (1st April – 30th September) for a relative wet growing season (2014, 'wet growing season'), an average growing season (2016, 'avg growing season') and an extremely dry growing season (2018, 'dry growing season'). Additionally, simulations were done for the reference situation ('base'), reference situation with deeper roots from 30 cm to 50 cm ('roots'), reference situation but the ditch level was raised from 150 cm-ss to 80 cm-ss ('ditch'), and the reference situation but the resistance to downward seepage increased from 800 d to 1200 d ('resist').

Changes in ditch level, hydraulic resistance to downward seepage, and changes in rooting depth affected ditch and pipe drainage fluxes, downward seepage and transpiration (Figure 4.7). Figure 4.7 shows the differences based on the growing season, the values in the following text are based on differences in the yearly water balance. First, deeper roots (50 vs 30 cm) require a less shallow groundwater level, resulting in reduced additional water supply (175 – 40 – 90 mm). This resulted in less ditch drainage (72 – 12 – 51 mm/y) and less downward seepage (57 – 6 – 29 mm/y, all for wet – avg – dry – wet growing season) (Appendix 4.6.1, Figure 4.10). Second, a raised ditch level (80 vs 150 cm-ss) caused a smaller head gradient between the ditch level and groundwater level, resulting in less water supply (75 – 33 – 87 mm/y) and less ditch drainage (215 – 266 – 251 mm/y). Because of a higher groundwater level, more pipe drainage (56 – 147 – 21 mm/y) occurred when the crest level is lowered. Lastly, downward seepage also increased (61 – 74 – 83 mm/y, all for wet – avg – dry – wet growing season) (Figure 4.7). Third, an increased hydraulic resistance (1200 d) to downward seepage compared to a field with a lower resistance (800 d) reduced water supply (10 – 15 – 26 mm/y). A higher resistance caused less downward seepage (101 – 115 – 117 mm/y), but more pipe drainage (27 – 42 – 10 mm/y) and ditch drainage (51 – 53 – 59 mm/y, all for wet – avg – dry growing season) (Figure 4.7).

4.3.3.2 Changes in relative transpiration

The drainage system and acceptance of oxygen and drought stress impacted the water supply and relative transpiration (and thus relative dry matter production or crop yield (De Wit, 1958)) (Figure 4.8A). Water supply and relative transpiration showed a linear effect (e.g. 2019), meaning transpiration decreases with increasing water supply. However, water supply and relative transpiration also showed a non-linear effect (e.g. 2015) because transpiration increased (reduced oxygen stress) while water supply decreased between CDSI-fix and CDSI-dyn0. Generally, CDSI-fix required most water (778 mm – 916 mm, 2014 vs 2018), as this strategy does not take into account the actual crop needs during the growing season, and thus resulted in the highest crop water availability (relative transpiration = 0.94 – 0.99, 2018 vs 2019) (Figure 4.8A). Acceptance of daily oxygen and drought stress (10 to 40%) resulted in lower water supply (0 – 835 mm, CDSI-dyn40$_{2021}$ vs CDSI-dyn10$_{2020}$) but of course also a lower yearly relative transpiration (0.67 – 0.99, CDSI-dyn40$_{2020}$ vs CDSI-dyn10$_{2014}$).

For the different drainage systems, the effect on the relative transpiration depends on the meteorological conditions (Figure 4.8A). Water supply ranges from 5 – 778 mm in a relatively wet growing season (2014) resulting in very minor effects on crop yield (relative transpiration ranges from 0.95 to 0.97). In an average growing season (2016): water supply ranges from 130 – 803 mm resulting in relative transpiration ranging from 0.87 to 0.98. Lastly, water supply ranges from 434 – 916 mm in an extremely dry year (2018) resulting in major effects on crop yield (relative transpiration ranges from 0.67 to 0.94). Logically no water supply resulted in the lowest yearly relative transpiration (0.55 – 0.95) (Figure 4.8A).

Overall, it seems that 200 mm water supply acts as a threshold: if 0 to 200 mm/y water supply is required, transpiration was roughly comparable (i.e. similar low drought stress) for the different drainage systems. A reason could be that the soil is wet enough in these growing seasons either because there is sufficient precipitation or because environmental factors are favourable (Figure 4.8). Furthermore, water supply could be high (700 mm/y), while plant water stress is still relatively high (relative transpiration ≈ 0.8). In those cases (very dry growing seasons) the water supply is apparently not large enough to raise the groundwater level to such a level that the crop water demand is met.

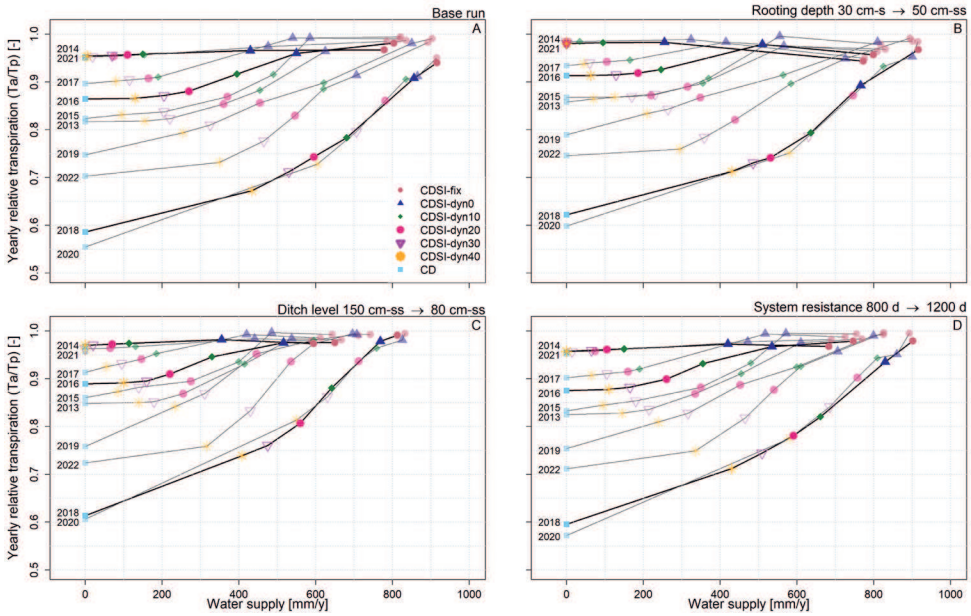


Figure 4.8: Yearly relative transpiration (actual transpiration divided by potential transpiration) and yearly water supply calculated with the SWAP model for 10 years (2013 – 2022) for controlled drainage with subirrigation (CDSI) using a fixed crest level of -50 cm and daily 5 mm water supply in the growing season (1st April – 30th September) ('controlled drainage with subirrigation (CDSI-fix)'), and CDSI with a dynamic crest level and dynamic water supply with acceptance of 0, 10, 20, 30, 40% oxygen and drought stress ('CDSI-dyn0', 'CDSI-dyn10', 'CDSI-dyn20', 'CDSI-dyn30', 'CDSI-dyn40'), and controlled drainage with a yearly crest level at -50 cm to retain water ('controlled drainage (CD)'). All calculations were performed for the base run (A), base run but rooting depth changed from 30 cm-ss to 50 cm-ss (B), base run but ditch level changed from 150 cm-ss to 80 cm-ss (C), and base run but resistance to downward seepage changed from 800 d to 1200 d (D).

Geohydrological and root characteristics impacted the water supply and thus yield reduction (Figure 4.8B, C and D). Changes in water supply and crop transpiration reduction were different per change in characteristic for the different drainage systems. Reducing water supply in CDSI-dyn20, CDSI-dyn30 and CDSI-dyn40 resulted in minor changes for relative transpiration. However, reducing water supply from CDSI-fix to CDSI-dyn0 and CDSI-dyn10 resulted in larger changes for relative transpiration.

First, a deeper rooting depth for CDSI-fix did not impact water supply (916 mm), while transpiration slightly increased (0.97 vs 0.98, shallow vs deeper roots). For CDSI-dyn0 the water supply reduced with 175 – 40 – 90 mm (wet vs avg vs dry growing season), while relative transpiration increased (+0.02, wet and avg growing season) and decreased (-0.01, dry growing season). For CDSI-dyn10 water supply reduced with 55 – 149 – 45 mm/y (wet vs avg vs dry growing season), providing a minor increase in relative transpiration (0.02 – 0.01 – 0.01, wet vs avg vs dry growing season). Thus, deeper roots resulted in major reductions in water supply (up to 175 mm), while maintaining relative transpiration or leading to a minor reduction. To properly compare the results, the crest level was kept at

50 cm-ss for CDSI-fix. However, for a deeper rooting depth H_{crest} could be set lower than 50 cm-ss in practice, leading to a lower water supply.

Second, a higher ditch level for CDSI-fix reduced water supply with 184 – 153 – 103 mm (wet vs avg vs dry growing season), while relative transpiration slightly increased with 0.01 - 0.05 (wet vs dry growing season) or decreased with 0.01 (avg growing season). For CDSI-dyn0 water supply reduced with 75 – 34 – 88 mm (wet vs avg vs dry growing season) while relative transpiration increased with 0.02 – 0.02 – 0.07 (wet vs avg vs dry growing season). For CDSI-dyn10 water supply reduced with 36 – 65 – 39 mm (wet vs avg vs dry growing season) while relative transpiration increased with 0.02 – 0.03 – 0.10 (wet vs avg vs dry growing season).

Third, a higher hydraulic resistance to downward seepage for CDSI-fix reduced water supply with 96 – 57 – 14 (wet vs avg vs dry growing season), while relative transpiration increased with 0.0 – 0.02 – 0.04 (wet vs avg vs dry growing season). For CDSI-dyn0 water supply reduced with 10 – 15 – 26 mm (wet vs avg vs dry growing season) while relative transpiration increased with 0.01 – 0.01 – 0.03 (wet vs avg vs dry growing season). For CDSI-dyn10 water supply reduced with 0 – 40 – 20 mm (wet vs avg dry growing season) while relative transpiration increased with 0.0 – 0.02 – 0.04 (wet vs avg vs dry growing season).
The geohydrological characteristics ‘ditch level’ and ‘hydraulic resistance to downward seepage’ are interchangeable with each other. Reduced drainage and downward seepage contributed to less loss of infiltrated water and thus less water supply, while maintaining crop water availability.

4.3.3.3 Changes in actual transpiration, drainage and downward seepage

The type of drainage system in combination with the acceptance of drought and oxygen stress determines the water supply and thus the effect on the main water balance components actual transpiration, total drainage (pipe + ditch drainage) and downward seepage. Figure 4.9 shows the water supply vs the differences in water balance components of an analysed drainage system (‘CDSI-fix’, ‘CDSI-dyn0’, ‘CDSI-dyn10’, ‘CDSI-dyn20’, ‘CDSI-dyn30’, ‘CDSI-dyn40’) minus controlled drainage (CD) of the base run. In addition, Figure 4.9 shows the changes in hydrological fluxes as result of deeper roots or a higher ditch level for the respective drainage systems.

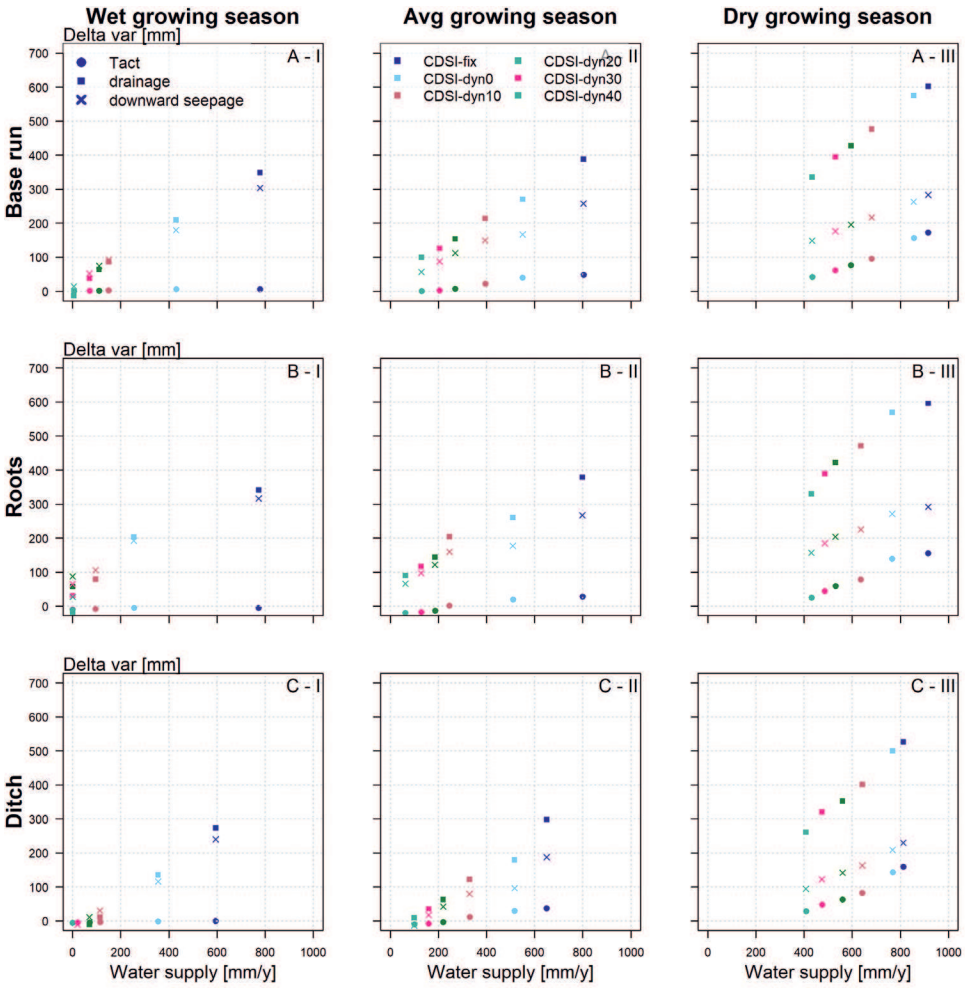


Figure 4.9: Change ('Delta') of actual transpiration ('Tact'), total drainage (pipe drainage + lateral drainage, 'drainage') and downward seepage as function of water supply. Delta is defined as the difference between controlled drainage of the base run minus a variation of a drainage system ('CDSI-fix', 'CDSI-dyn0', 'CDSI-dyn10', 'CDSI-dyn20', 'CDSI-dyn30', 'CDSI-dyn40') for three scenarios ('Base run', 'Roots', 'Ditch'). The scenarios are base run ('base run', A), base run but rooting depth changed from 30 cm-ss to 50 cm-ss ('Roots', B), base run but ditch level changed from 150 cm-ss to 80 cm-ss ('Ditch', C). All calculations were performed for a wet growing season (2014, 'I'), an average growing season (2016, 'II'), and a dry growing season (2018, 'III'). Note: for B-I holds that Delta Tact, drainage and downward seepage values of CDSI-dyn20, CDSI-dyn30, CDSI-dyn40 are identical.

The hydrological fluxes depend on variations in meteorology (a relative wet, average, and extremely dry growing season), variations in drainage systems and variations in rooting depth and ditch level. Wetter growing seasons required less water supply, with minor advantages for actual transpiration. Conversely, drier growing seasons required more water supply with major advantages for actual transpiration. This means that in a relatively wet growing season, changes in hydrological fluxes (actual transpiration, drainage and downward seepage) were small (0 – 100 mm/y) compared to an extremely dry growing

season (0 – 600 mm) for the drainage systems CDSI-dyn20, CDSI-dyn30 and CDSI-dyn40 (Figure 4.9). However, for the drainage systems CDSI-fix, CDSI-dyn0 and CDSI-dyn10 the hydrological changes were relatively large in a wet growing season (0 – 400 mm) compared to a dry growing season (0 – 600 mm).

The distribution of water supply over the hydrological fluxes differed strongly between meteorological conditions. Hydrological fluxes were large for the base run CDSI-fix and small for the base run CDSI-dyn40 (Figure 4.9). Therefore, all values in the following text are values of the base run of CDSI-dyn40 vs the base run of CDSI-fix. The values for the base run CDSI-fix and CDSI-dyn0, CDSI-dyn10, CDSI-dyn20 and CDSI-dyn30 are all within the presented ranges. First, in a relatively wet growing season, a very minor portion of the total water supply (0 – 778 mm, CDSI-dyn40$_{\text{base run}}$ vs CDSI-fix $_{\text{base run}}$) went to increased transpiration (0 – 6 mm, CDSI-dyn40$_{\text{base run}}$ vs CDSI-fix $_{\text{base run}}$). Most water left the system as drainage (0 – 348 mm, CDSI-dyn40$_{\text{base run}}$ vs CDSI-fix $_{\text{base run}}$) or downward seepage (14 – 303 mm, CDSI-dyn40$_{\text{base run}}$ vs CDSI-fix $_{\text{base run}}$). Second, in an average growing season, a minor portion of the total water supply (0 – 803 mm) went to increased transpiration (0 – 40 mm), but most water left the system as drainage (10 – 388 mm) or downward seepage (56 – 257 mm). Thus, in an average growing season, transpiration slightly increased by supplying water. Lastly, in an extremely dry growing season, some water supply (0 – 916 mm) went to transpiration (42 – 156 mm), while some water left the system as drainage (335 – 601 mm) or downward seepage (148 – 283 mm). Thus, in an extremely dry growing season, transpiration substantially increased by supplying water.

Finally, Figure 4.9 shows a maximum (upper threshold) for transpiration in an average growing season (for the base run, roots and ditch) and in the dry growing season (for the ditch run). Reaching the upper threshold for transpiration means that more water supply only leads to more drainage and downward seepage and almost no extra transpiration.

4.4 Discussion

This experiment and analysis is the first, to the best of our knowledge, that i) compared the hydrological fluxes of four different drainage systems, ii) indicated the impact of ditch level, resistance to downward seepage and crop characteristics on required water supply for CDSI systems, and iii) showed the effect of acceptance of crop stress in relation to the required water supply for CDSI. The combination of current field conditions and the weather forecast adds complexity to CDSI modelling. However, it results in a better understanding of to what extent the water requirement of CDSI systems can be reduced.

The hydrological consequences are strongly related to the type of drainage system. From conventional drainage to controlled drainage less water is discharged to the surface water, which results in higher groundwater levels (100 – 250 cm-ss vs 50 – 120 cm-ss). Important

is that sufficient precipitation is needed for retention to maintain the groundwater levels (Ramoska et al., 2011; Skaggs et al., 2012a). Furthermore, CD requires proper management. The crest level needs to be lowered in time, otherwise oxygen stress situations could occur as seen in 2016 (Figure 4.4). Conversely, the crest level must be kept high, so that water is retained in winter for the next summer, like in 2019 (Figure 4.4). From CD to CDSI-fix drought stress decreased due to water supply as also found in Singh et al. (2022). However, drainage, downward seepage and the required water supply can be high as found in earlier literature (De Wit et al., 2022; Smith et al., 1985). From CDSI-fix to CDSI-dyn water supply reduced, while crop yield was maintained or minor reductions occurred (Figure 4.8).

The differences in water demand varied in this study between 0 to 916 mm/y for the different drainage systems. These water supply values were representative for CDSI-fix systems for agricultural fields in the Dutch sandy Pleistocene uplands (De Wit et al., 2024c). However, important to notice is that the water demand strongly depends on, among other things, i) the geohydrological characteristics of a field (e.g. ditch level, soil hydraulic properties, regional water management, crop characteristics), ii) whether a source for water supply is available, and iii) how CDSI is managed (fixed or dynamic), as explained in detail in this chapter. Furthermore, although the results in this chapter were based on a modelling study, De Wit et al. (2024c) showed that the SWAP model was able to reproduce the field measurements for different CDSI system field experiments. This indicates that the model simulations give a good indication of water supply for each drainage system. The model parameterization, including the scenarios, are tailored to the field pilots in the Netherlands. However, the model setup and modelling approach is generally applicable, allowing to extend the analysis to other regions in the world. In addition, the modelling approach shows the large variability of hydrological fluxes which occur in different meteorologically years. Field experiments usually span a limited number of meteorologically years and are unable to reveal this temporal variability of hydrological fluxes.

Drainage systems (from CD to CDSI) are installed worldwide with different control techniques. A fixed H_{crest} is often used (Bonaiti and Borin, 2010; Hooghoudt, 1952; Jouni et al., 2018), but also resulted in a high water supply (400 mm, Hooghoudt (1952)). Also Tan et al. (2007) used a fixed H_{crest} of 40 cm-ss, but initiated subirrigation only when the crop height was approximately 60 cm and only applied for weeks in July and August. For those weeks, water supply was 287 – 203 mm (2001 vs 2022). Mejia et al. (2000) compared three pilots side by side (free drainage, CDSI-fix at 50 cm-ss (CDSI-fix$_{50}$) and CDSI-fix at 75 cm-ss (CDSI-fix$_{75}$)). Yield increased in 1995 with 13.8 and 2.8% (CDSI-fix$_{50}$ and CDSI-fix$_{75}$, both compared to free drainage) and in 1996 with 6.6 and 6.9% (CDSI-fix$_{50}$ and CDSI-fix$_{75}$, both compared to free drainage). Total water supply for both treatments (CDSI-fix$_{50}$ and CDSI-

fix_{75}) added together was 223 mm in 1995 and 248 mm in 1996. The study only shows the summed water supply for both treatments per year, which limits the interpretation of the relation between water supply, crest height and plant transpiration. Jouni et al. (2018) described that irrigation gifts lowered when it is based on *SMC* measurements (1017 vs 980 mm irrigation – CDSI-fix at 70 cm-ss vs CDSI-dyn based on daily measured *SMC*), while crop yield increased (27 – 41% for wheat, 18 – 25% for barley and 19 – 25% for maize, highest crop yield corresponds with CDSI-dyn pilots). So, the water supply is high compared to the values in this chapter. However, the increased transpiration corresponds to the results in this chapter.

There is an international search for the implementation of crest control and water supply reduction systems. Bengtson et al. (1993) described a simple model, which can be used to understand daily fluctuations in the groundwater level, allowing the level in the control put to be adjusted manually. Fouss and Cooper (1988) described a model study to indicate the reduction of water supply for subirrigation based on a combination of DRAINMOD modelling (Skaggs et al., 2012b) and weather forecasts. Their study focused on maintaining a fixed drainage level, but subirrigation was stopped if a given rainfall probability index was exceeded. The water supply for subirrigation was reduced by 12 to 21% compared to continuous subirrigation, while crop yield remained the same. Afterwards it turned out that the automatic control method could work, but the area they used for the model exercise was not suitable for automatic drainage (Stuyt, 2013). In recent years, a CDSI-dyn system has been made technically operational in the Netherlands (Appendix 4.6.2, Figure 4.11).

It is important to realize that the desired effects of CDSI depend on the purpose of CDSI, local and regional scale components and meteorological conditions (De Wit et al., 2022). Drainage systems are generally installed to manage water quantity aspects and variations like controlled drainage are also intended to improve water quality. The technical design relates to the purpose and therefore the design varies in literature, e.g.: drain spacing could range from 8 (Bonaiti and Borin, 2010) to 80 m (Jouni et al., 2018) and drain depth could range from 0.9 (Bonaiti and Borin, 2010) to 2.0 m (Jouni et al., 2018). Therefore, correct and responsible implementation of drainage systems requires knowledge about local and regional scale components. All in all, controlled drainage (with subirrigation) systems are installed worldwide, but for comparing literature across countries, it is important to have the purpose of CDSI and local and regional components in mind.

4.5 Conclusion

The shifting drainage strategy in the Netherlands over the last decades (conventional to controlled drainage to fixed CDSI) relates to the corresponding shifting water strategy (from discharge, to discharge + retention, to discharge + retention + recharge). Controlled drainage with subirrigation (CDSI) is a viable measure to supply, retain or discharge water.

However, due to the changing water strategy, crop yield could increase, but the freshwater availability is under pressure due to the required water supply for subirrigation. This study confirms that dynamic control of CDSI can decrease the water supply compared to fixed CDSI systems. Dynamic control of CDSI takes into account the actual crop water needs based on the actual soil moisture conditions and the weather forecast.

Water supply may reduce even further when taking into account environmental characteristics, crop characteristics and crop management. Firstly, higher ditch water levels reduce the head difference between the surface water level and the groundwater level, and herewith drainage losses. Secondly, a higher hydraulic resistance to downward seepage results in a lower water demand and supply. Thirdly, deeper roots result in a lower water demand. So, in order to reduce the water demand and supply CDSI systems could be installed in areas where ditch levels can be aligned to the raised groundwater level, where the subsoil has some resistance to downward seepage (e.g. loamy layers) and when crops with deeper roots (e.g. > 50 cm) are present. The water demand reduces even further by accepting minor reductions in crop yield compared to the situation without CDSI. However, the water demand is strongly related with the meteorological conditions; water demand reduces primarily in eventually wetter and average years and only slightly in very dry years.

In general, a CDSI system causes a higher groundwater table such that soil water availability for crops and herewith actual transpiration increases, due to capillary rise. However, an upper threshold might be reached where extra water supply increases total drainage and downward seepage, but extra crop transpiration is limited. Therefore, it is important to be able to estimate the water supply that actually contributes to additional transpiration. The model set-up in this study can help with that. This is important as CDSI systems manage the groundwater level and herewith crop water availability, but also require water and affect drainage and downward seepage. They should thus be implemented in such a way that they fit within both the local (field scale) and regional water management. The results and insights of this study support responsible implementation of CDSI systems.

4.6 Appendix

4.6.1 Appendix: Hydrological consequences for simulations with larger rooting depth

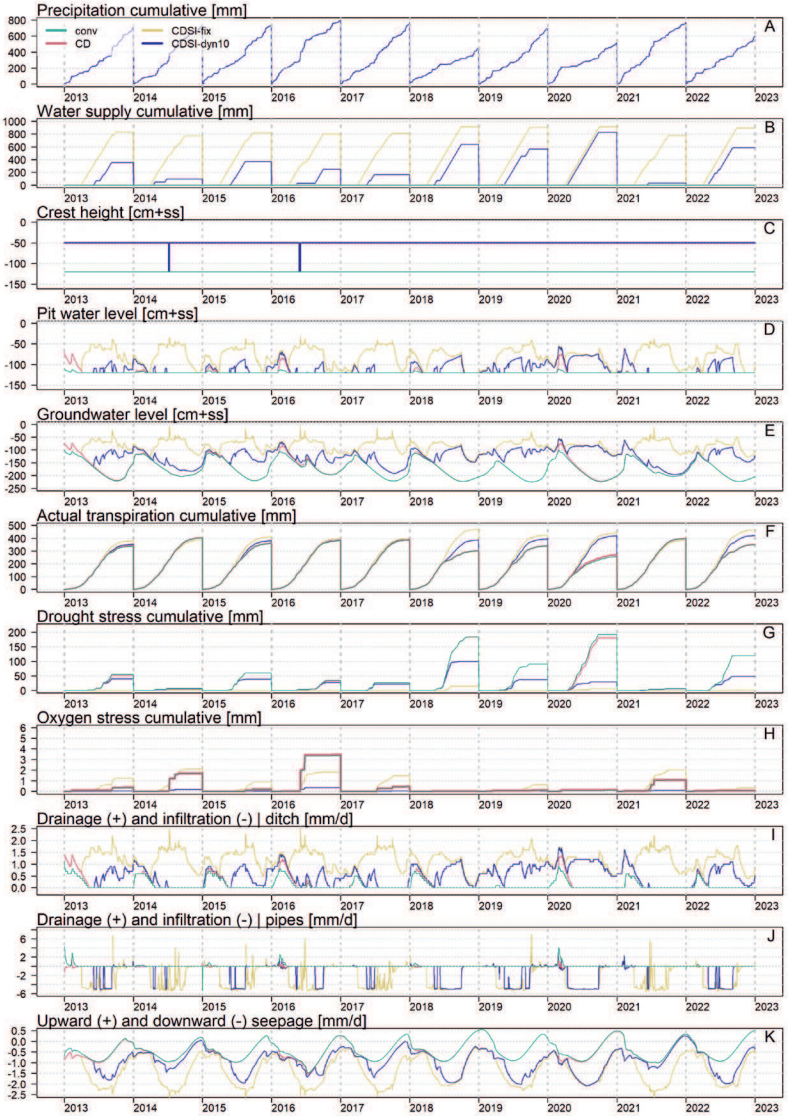


Figure 4.10: Overview of measured cumulative precipitation of the automatic KNMI station Arcen (A), cumulative water supply (B), crest height (C), pit water level (D), groundwater level (E), cumulative actual transpiration (F), cumulative drought stress (G), cumulative oxygen stress (H), drainage and infiltration of the ditch (I) and drainage pipes (J), and upward and downward seepage (K). All components are calculated with the drainage systems conventional situation with a yearly H_{crest} at -120 cm to drain water ('conv'), controlled drainage with a yearly crest level at -50 cm to retain water ('CD'), controlled drainage with subirrigation (CDSI) with a fixed crest level of -50 cm and daily 5 mm water supply in the growing season (1st April – 30th September) ('fix') and CDSI with a dynamic crest level and dynamic water supply with acceptance of 10% oxygen and drought stress ('dyn10%'). All results are based on simulations with a rooting depth of 50 cm-ss.

4.6.2 Appendix: Implementation of CDSI-dyn system in the field experiment in Stegeren

A CDSI-dyn system has been made technically operational in a field experiment in Stegeren (The Netherlands). A connection has been set up between the field measurements, the algorithm (section 4.2.2.3) and the daily weather forecast. To do so, three steps were added to the algorithm (Figure 4.11).

- Online calibration step, based on field measurements, aims to estimate the optimal hydraulic head in the deep aquifer over the last 31 days. Online calibration is required to capture the seasonality in the hydraulic head (Visser et al., 2006).
- Online data assimilation, based on the field measurements of the last day, aims to estimate the best state of the current soil water column over the last day. Online data assimilation is required to find the most accurate initial state for the forecast step (Visser et al., 2006).
- Forecast step, based on field measurements and weather forecast, aims to forecast the hydrological conditions and plant stress for the following 10 days. Field measurements are groundwater table and soil moisture content (20 cm, 40 cm, 60 cm depth), daily weather forecast is used from Open Weather Forecast (https://openweathermap.org/). In the forecast step, the optimization routine presented in the current study is applied, providing a new H_{crest} and W_{supply}, subsequently set in the field system.

Although technically the system was fully operational, the geohydrological characteristics of the area resulted in excessive downward seepage, limiting the required increase in groundwater level for improved plant water availability for this specific site (De Wit et al., 2024c).

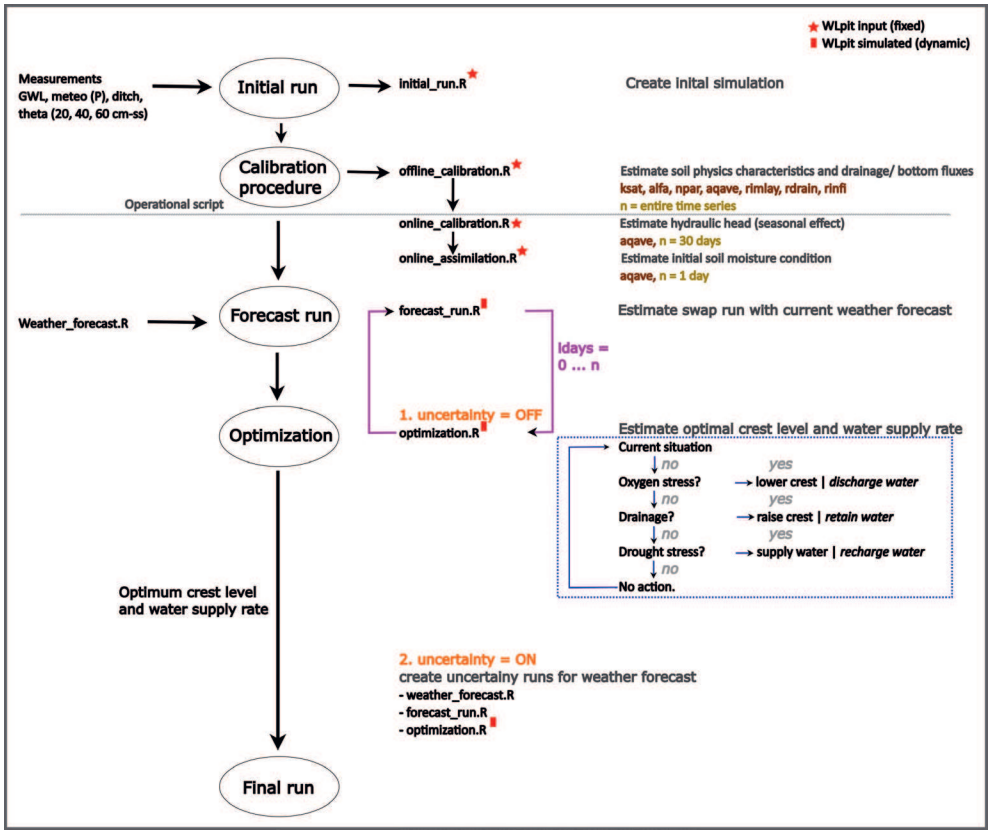


Figure 4.11: CAD-algorithm consisting of five steps; 1) initial SWAP run, 2) calibration procedure in which SWAP is calibrated with PEST based on field measurements, 3) forecast run including the weather forecast, 4) optimization run, and 5) the final SWAP run. The SWAP simulations differ between fixed pit levels (indicated with a red star) and a dynamic pit level (indicated with a red rectangle).

5

CHAPTER 5

SUBSURFACE IRRIGATION IN REGIONAL WATER MANAGEMENT: A SYSTEM DYNAMICS APPROACH TO SUPPORT DECISION-MAKING

This chapter is based on the publication:
De Wit J.A., van Dam J.C., Heijmans T.H.H., van Huijgevoort M.H.J., Ritsema C.J., Bartholomeus R.P. (2026) Subsurface Irrigation in Regional Water Management: A System Dynamics Approach to Support Decision Making. Water Resources Management 40:113. DOI: https://doi.org/10.1007/s11269-025-04393-2.

Highlights

- Local scale CDSI requirements impact regional water supply and demand.
- Upscaling CDSI systems show nonlinear hydrological effects.
- Three critical phases related to regional water supply determine CDSI-upscaling possibilities.
- System dynamics modelling could bridge the knowledge gap between farmers and policymakers.

Abstract

Controlled drainage with subirrigation (CDSI) using surface water contributes to freshwater availability by recharging, retaining and discharging water. However, CDSI systems affect regional hydrological fluxes, which requires adequate regional planning and management. This study aims to i) investigate to what extent regional upscaling of CDSI can be supported in relation to surface water availability, using a system dynamics model (SDM) and ii) identify how an SDM can support decision making of water management authorities. An SDM was developed to simulate changes in hydrological fluxes and water levels resulting from CDSI upscaling from the local to the regional scale. An SDM was used as it is able to capture key non-linear feedbacks within the water system, such as those between i) surface water and groundwater, ii) groundwater and unsaturated zone, iii) regional water supply and weir management. The model provides insight into changes in hydrological fluxes due to CDSI upscaling, without long computational times and the complexities of spatially distributed models. Simulations show non-linear propagation of hydrological fluxes, where three phases can be identified for different degrees of upscaling: i) sufficient surface water availability, ii) surface water availability decreases due to subirrigation, and iii) insufficient water availability due to overexploitation. These phases are related to regional and local water management strategies controlled by water management authorities and farmers, and to geohydrological characteristics. In conclusion, the SDM can support early-stage strategic planning on the feasibility of CDSI upscaling and facilitate discussions between stakeholders by efficiently visualizing and quantifying associated hydrological effects.

Keywords

Controlled drainage, local scale, regional scale, subirrigation, system dynamics modelling, Vensim, water management.

5.1 Introduction

The mismatch between water demand and supply is increasing due to climatic and socioeconomic changes (Pronk et al., 2021). In temperate climates, regional water management strategies are therefore shifting from exclusively drainage, to drainage, retention and recharge (Bartholomeus et al., 2023). This shift is also reflected at the local scale where conventional drainage systems, historically installed to discharge water during wet periods (De Wit et al., 2022) are changed to controlled drainage (CD) systems that both retain and discharge water, and to controlled drainage with subirrigation (CDSI) systems (Figure 5.1), which can retain, recharge, and discharge water.

A CDSI system is a field scale measure which aims to repair the imbalance of water demand and water supply in agriculture. However, CDSI also affects the regional water system. CDSI used for subirrigation raises the groundwater level (*GWL*), thereby enhancing water availability for crop growth through capillary rise. However, CDSI implementation alters several water balance components (Skaggs et al., 2012a; Wesström et al., 2014), as the volume of supplied water ranges from approximately 200 to 900 mm/year, depending on weather conditions, geohydrological characteristics, crop type and adaptive pump management (De Wit et al., 2024b). Part of the supplied surface water improves hydrological conditions for crops (Singh et al., 2022), while another recharges regional groundwater or is discharged to surface water. For regional water management authorities, it is important to understand how field scale CDSI applications propagate through the regional water system and to what extent CDSI upscaling by farmers can be supported through surface water management.

CDSI can contribute to regional water management strategies aimed at reducing drainage and increasing water retention. However, CDSI may increase pressure on surface water availability during drier periods. As surface water is not infinitely available, the challenge is to balance water use for nature and across societal sectors. This requires embedding field measures such as CDSI into regional water strategies. While sufficient water may be available when CDSI is applied on a few hectares (De Wit et al., 2024b; De Wit et al., 2024c), regional upscaling demands insight into: i) the percentage of the area to which CDSI could be scaled, considering non-linear hydrological feedbacks and regional water availability, and ii) how to engage farmers and policymakers in discussion about the possibilities and limitations of CDSI upscaling?

Hydrological models range from detailed spatially distributed models to black box models, with lumped approaches in between. Spatially distributed models are most suitable for detailed analyses, such as identifying exact locations for upscaling CDSI. Lumped system dynamics models (SDMs) are useful for initial assessments of the feasibility of implementing a measure (Zhou et al., 2025); in this study, an SDM is applied to assess the upscaling of CDSI in relation to its impact on the magnitude of hydrological fluxes. SDMs are particularly valuable for understanding non-linear behavior of interactive, complex systems, and for supporting policy decisions and system design (Javanbakht-Sheikhahmad et al., 2024; Mashaly and Fernald, 2020; Phan et al., 2021). SDMs are extensively used for rainfall-runoff

modelling (Brauer et al., 2014), but can also simulate groundwater systems if hydrological properties are well conceptualized (Ejaz et al., 2022). However this has rarely been done (Phan et al., 2021). SDMs have been applied to simulate hydrological fluxes related to irrigation (Khan et al., 2009) and related to subsurface drainage systems combined with irrigation (Matinzadeh et al., 2017). To the best of our knowledge, no SDM has yet been developed to assess the regional upscaling of CDSI, despite the fact that both the non-linear effects of upscaling and the need for decision support tools call for such a novel approach. Therefore, the aim of this study is to i) investigate to what extent regional upscaling of CDSI can be supported using an SDM in relation to surface water availability and ii) identify how an SDM can support water management authorities in decision making.

The SDM setup is a simple but comprehensive model that includes all key aspects and feedbacks of a CDSI system. Detailed knowledge about these aspects is available from previous field experiments and numerical modelling studies (De Wit et al., 2024b; De Wit et al., 2024c), which serve as a reference for comparison. The SDM has been applied across varying percentages of upscaling, regional water management strategies, and geohydrological settings to identify thresholds at which CDSI can or cannot be implemented.

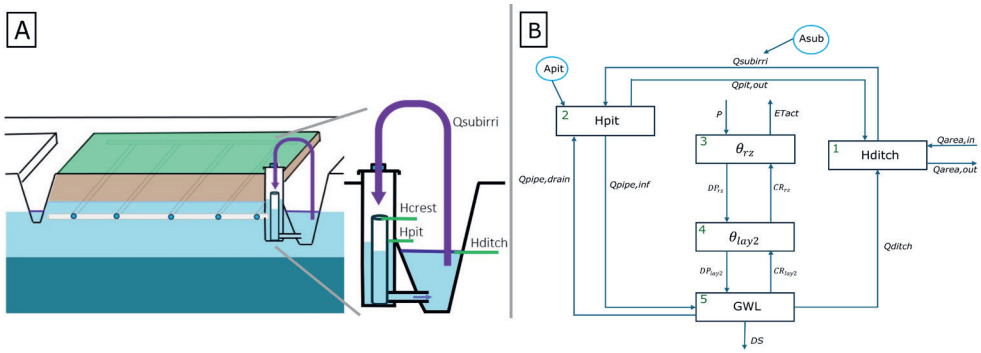


Figure 5.1: A: Schematization of a CDSI system with the infiltration/ drainage pipes in grey (dotted) lines. B: CDSI in a system dynamics approach with state variables (square), hydrological fluxes (arrows) and scaling factors (circle).

5.2 Methods

5.2.1 General CDSI setup in SDM based on an experimental site

The general setup of the SDM for regional evaluation of CDSI upscaling includes the key elements and hydrological fluxes influenced by a CDSI system embedded within a regional context (Figure 5.1). In general, a CDSI system consists of a control pit where external water (from a ditch) for subirrigation is supplied. The control pit is connected to a collector pipe, which is in turn connected to the infiltration/drainage pipes, which is oriented perpendicular to the collector pipe. Water flows through the pipes and enters the groundwater via perforated holes. Soil moisture reaches the plant rooting zone through capillary rise from the groundwater. Therefore, the SDM contains the water reservoirs 'ditch' (1), 'control pit' (2), 'groundwater' (5), 'rooting zone' (rz, 3) and 'second layer of the

unsaturated zone' (lay2, 4) (Figure 5.1). These reservoirs are connected via flows to simulate the hydrological fluxes. Finally, a scaling factor is included to upscale the CDSI covered area within the SDM.

The SDM is programmed in Vensim (version: Vensim PLE Plus 9.0.1x64). System components are described as state variables connected by hydrological fluxes and supported by auxiliary variables (e.g. wilting point, drain spacing). The SDM is based on a field study conducted in the southeast of the Dutch sandy Pleistocene uplands (51º27'N, 5º57'E) where CDSI was applied between 2017-2024. This field experiment was used as a base because i) the hydrological consequences of CDSI on field scale were known in detail for this location (De Wit et al., 2024c), ii) the location is a field site with average suitability for subsurface irrigation in terms of geohydrological characteristics in the sandy Pleistocene uplands of the Netherlands (De Wit et al., 2024c), and iii) there are discussions between local and regional stakeholders on the risks and benefits of regional CDSI upscaling.

The SDM setup was based on a field experiment including measurements and numerical modeling (De Wit et al., 2024b; De Wit et al., 2024c) using the agro-hydrological field scale model SWAP (version 4.0.1) (Heinen et al., 2024; Kroes et al., 2017) and regional characteristics of the area. The model was applied with the following settings: total area is 3,500,000 m^2, surface water enters the area with a constant rate 2,000 m^3/d throughout the year, total ditch area was 259,200 m^2 with a ditch depth of 2 m and an initial surface water level of 1.1 meter below soil surface (m-ss) (input from Water management authority Limburg). Initial water level in the control pit is 0.8 m-ss, crest level is 0.52 m-ss from 1st October to 31st March and 0.50 m-ss from 1st April to 30th September. This small difference is included to avoid modelling of pipe drainage while subirrigation is applied. Subirrigation is a maximum of 5 mm/d in the growing season. The preferred *GWL* to reach throughout the growing season is 0.8 m-ss. This means that subirrigation is applied as long as sufficient surface water is available and the *GWL* does not exceed the preferred *GWL*. Meteorological data for precipitation and reference evapotranspiration was obtained from the nearby weather station Arcen (nr. 391) of the Royal Netherlands Meteorological Institute. The soil was classified as a 'weak loamy, very fine to moderately fine sandy' soil ('O02' soil, Heinen et al. (2020)). The initial soil moisture content (*SMC*) of both the rooting zone and the unsaturated zone is 0.23 m^3/m^3. The rooting zone is 0.30 m. Initial *GWL* is 0.80 m-ss, the storage coefficient is 0.10 (CultuurtechnischeVereniging, 1988). The simulated time step is one day.

5.2.2 CDSI schematisation in Vensim

The general water reservoirs ('state variables') are connected via flows to simulate the hydrological fluxes. The state variables are explained below with associated flows. The underlying calculations and description of the SDM are described in detail in the online supplementary material.

5.2.2.1 Regional water management

The modelled regional area is primarily a water supply area that is intensively managed with water distributed via ditches. Outflow occurs when the ditch level exceeds the weir level. Surface water level (H_{ditch}) (m-ss) is described as:

$$H_{\mathrm{ditch,t}} = H_{\mathrm{ditch,t-1}} + \frac{Q_{\mathrm{ditch,t}} + Q_{\mathrm{area_in,t}} + Q_{\mathrm{pit_out,t}} - Q_{\mathrm{area_out,t}} - Q_{\mathrm{subirri,t}}}{A_{\mathrm{ditch}}} \quad [1]$$

where $H_{\mathrm{ditch,t-1}}$ is ditch level at timestep t-1 (m), Q_{ditch} is ditch drainage (m^3), $Q_{\mathrm{area_in}}$ is regional inflow (m^3), $Q_{\mathrm{pit_out}}$ is water drained from the pit to the ditch (m^3), $Q_{\mathrm{area_out}}$ is regional outflow (m^3), Q_{subirri} is water abstracted for subirrigation (m^3), A_{ditch} is ditch area (m^2). Surface water exits the ditch as subirrigation or outflow over the weir. H_{ditch} raises through regional inflow or through ditch drainage. Q_{subirri} occurred from 1st April to 30th September when $GWL < GWL_{\mathrm{pref}}$ and when $H_{\mathrm{ditch}} > H_{\mathrm{ditch_min}}$, i.e. when surface water is available as source for subirrigation.

5.2.2.2 CDSI systems: control pit

The control pit is key in the CDSI setup because it determines the drainage and infiltration level of a field. Pit water level (H_{pit}) is estimated as:

$$H_{\mathrm{pit,t}} = H_{\mathrm{pit,t-1}} + \frac{Q_{\mathrm{pipe_drain,t}} + Q_{\mathrm{subirri,t}} - Q_{\mathrm{pit_out,t}} - Q_{\mathrm{pipe_inf,t}}}{A_{\mathrm{pit}}} \quad [2]$$

where $H_{\mathrm{pit,t-1}}$ is level in the control pit at timestep t-1 (m), $Q_{\mathrm{pipe_drain}}$ is pipe drainage (m^3), Q_{subirri} is water supply (m^3), $Q_{\mathrm{pit_out}}$ is pit drainage (m^3), $Q_{\mathrm{pipe_inf}}$ is pipe infiltration (m^3), A_{pit} represents the total area in the underground system where subirrigation is applied, including the pit, pipes and soil around the pipes. A_{pit} is estimated as $A_{\mathrm{pit}} = 0.19 * A_{\mathrm{sub}}$ (m^2), where A_{sub} is the area with CDSI fields (m^2). The factor 0.19 was estimated based on manual calibration of the simulated H_{pit} to the measured H_{pit}. Furthermore, H_{pit} is controlled via the crest height (H_{crest}). The control pit retains groundwater when $H_{\mathrm{pit}} < H_{\mathrm{crest}}$ & $Q_{\mathrm{subirri}} = 0$, recharges groundwater when $H_{\mathrm{pit}} < H_{\mathrm{crest}}$ & $Q_{\mathrm{subirri}} > 0$, and discharges water when $H_{\mathrm{pit}} > H_{\mathrm{crest}}$.

5.2.2.3 Rooting zone

The soil water system was split into the rooting zone, the second layer of the unsaturated zone and the saturated zone. The soil moisture content in the rooting zone (θ_{rz}) (m^3/m^3) is estimated as:

$$\theta_{\mathrm{rz,t}} = \theta_{\mathrm{rz,t-1}} + \frac{P_{\mathrm{t}} + CR_{\mathrm{rz,t}} - ET_{\mathrm{act,t}} - DP_{\mathrm{rz,t}} - Q_{\mathrm{pond,t}}}{Dr_{\mathrm{rz}} * A_{\mathrm{sub}}} \qquad \theta_{\mathrm{wp}} < \theta_{\mathrm{rz}} < \theta_{\mathrm{sat}} \quad [3]$$

where $\theta_{\mathrm{rz,t-1}}$ is the SMC in the rooting zone at timestep t-1 (m^3/m^3), P is precipitation (m^3), CR_{rz} is capillary rise from the second layer to the rooting zone (m^3), ET_{act} is actual evapotranspiration (m^3), DP_{rz} is deep percolation from the rooting zone to the second layer (m^3), Q_{pond} is ponding layer that disappears as runoff (m^3), Dr_{rz} is the rooting zone depth (m). Furthermore, ET_{ref} was multiplied by a crop factor to calculate potential evapotranspiration (ET_{pot}). Next, ET_{pot} was multiplied by a reduction factor for reduced root water uptake due to water limitation, to calculate ET_{act}. As a linear relationship is

assumed between relative transpiration and relative crop yield (De Wit, 1958), $ET_{\mathrm{act}} < ET_{\mathrm{pot}}$ indicates that crop water demand cannot be met and thus drought stress occurs.

5.2.2.4 Second unsaturated zone layer

The second layer of the unsaturated soil is between the rooting zone and GWL. Therefore, the depth of this layer (Dr_{lay2}) varies depending on the GWL. SMC in the second layer (θ_{lay2}) is estimated as:

$$\theta_{\mathrm{lay2,t}} = \theta_{\mathrm{lay2,t-1}} + \frac{\mathrm{CR_{lay2,t}} - \mathrm{CR_{rz,t}} + \mathrm{DP_{rz,t}} - DP_{\mathrm{lay2,t}}}{Dr_{\mathrm{lay2,t}} * A_{\mathrm{sub}}} \qquad \theta_{\mathrm{wp}} < \theta_{\mathrm{lay2}} < \theta_{\mathrm{sat}} \quad [4]$$

where $\theta_{\mathrm{lay2,t-1}}$ is the SMC in the second layer of the unsaturated soil at timestep t-1 (m^3/m^3). Water leaves the upper boundary of the second layer as CR_{rz} and enters the second layer as DP_{rz}. Water exits the lower boundary as DP_{lay2} and enters as CR_{lay2}.

5.2.2.5 Saturated zone

The saturated zone is between the second layer of the unsaturated zone and 5 m depth (total depth of the soil column). The upper boundary of the saturated zone represents the GWL, estimated by

$$GWL_{\mathrm{t}} = GWL_{\mathrm{t-1}} + \frac{DP_{\mathrm{lay2,t}} + Q_{\mathrm{pipe_inf,t}} - CR_{\mathrm{lay2,t}} - Q_{\mathrm{ditch_drain,t}} - Q_{\mathrm{pipe_drain,t}} + DS_{\mathrm{t}}}{A_{\mathrm{sub}}} * \frac{1}{S} \quad [5]$$

where $GWL_{\mathrm{t-1}}$ is the GWL at timestep t-1 (m-ss), S is the storage coefficient (-) and DS is seepage (m^3).

5.2.2.6 Scaling area with CDSI

A scale factor is included in the SDM to scale the percentage of subirrigation area. In the base model, a CDSI field located along a ditch is simulated. CDSI is then upscaled in defined percentages along to the ditch, relative to the base situation. Subirrigation is applied from one control pit. All hydrological fluxes and water reservoirs (m^3) are scaled according to the subirrigation area. Fields without subirrigation are not explicitly included in the model, based on the assumption that fluxes in these fields remain unchanged compared to the base model.

5.2.3 Field scale model SWAP to validate SDM

The SDM results of the base run were compared to the SWAP results (De Wit et al., 2024c) using the Kling-Gupta efficiency (KGE, Gupta et al. (2009)) and root mean square error (RMSE). SWAP is a 1D, process-based numerical model combining soil water flow (unsaturated zone, saturated zone and drainage management), root water uptake and crop growth, focusing on field scale. The parameterization of the SWAP model of De Wit et al. (2024c), calibrated and validated against field measurements, was slightly modified to allow comparison to the SDM. With respect to the published SWAP modeling, this includes changes in H_{crest}, H_{ditch}, soil profile (homogeneous O02 soil, Heinen et al. (2020)), the soil evaporation coefficient of Black was set to 0.80 and critical limits for root water uptake according to Feddes (1982) were set to h_1 = 100 cm, h_2 = 0 cm, h_3 = -100 cm, h_4 = -16000 cm.

5.2.4 Scenarios

CDSI was simulated using varying implementation scales of subirrigation, combined with subtle differences in geohydrological characteristics. First, the percentage of subirrigation of the total area is adjusted from 1.08% (field experiment area) to 10%, 20%, 25%, 40%, 50%, 60%, 80%, 90% and 99% with the goal to understand the propagation of CDSI effects through different components of the water system and the effect of upscaling. All other scenarios are simulated with 50% subirrigation of the total area. These scenarios use the following values: i) inflow of surface water into the ditch to increase regional water availability: 2000 m^3/d, 3000 m^3/d, 4000 m^3/d, 5000 m^3/d and 6000 m^3/d; ii) drainage resistance to the ditch: 350 d, 500 d, 650 d, 800 d, 1000 d, 1200 d; iii) weir height (H_{weir}): 1.5 m-ss, 1.3 m-ss, 1.1 m-ss, 0.9 m-ss, 0.7 m-ss and 0.5 m-ss to drain less groundwater and increase water storage in the ditch; iv) minimum H_{ditch}: 1.9 m-ss, 1.7 m-ss, 1.5 m-ss, 1.3 m-ss, 1.1 m-ss, 0.9 m-ss, 0.7 m-ss and 0.5 m-ss. H_{weir} was set to 0.5 m-ss for the H_{ditch} scenarios; v) preferable *GWL* for subirrigation: 1.3 m-ss, 1.1 m-ss, 0.9 m-ss, 0.8 m-ss, 0.7 m-ss, 0.5 m-ss. These scenarios were primarily aimed at indicating the hydrological effects of CDSI upscaling. The variation due to differences in geohydrological characteristics within a scenario can be interpreted as a sensitivity analysis.

5.3 Results

5.3.1 SDM and SWAP modelling of CDSI systems on a local scale

The measured precipitation ranges between 700 to 800 mm in 2013-2017 and 2021 and ranges between 445 to 602 mm in the drier years 2018-2020, 2022 (Figure 5.2A). Simulated annual subirrigation ranges from 525 mm in 2016 to 665 mm in 2022, depending on yearly meteorological conditions. The KGE was 0.95 and the RMSE 31.9 mm (Figure 5.2A) indicating acceptable model performances.

H_{pit} (Figure 5.6, Figure 5.7D) and *GWL* are raised with roughly 1 m due to subirrigation in both the SDM and SWAP model (Figure 5.2B). In the SDM, the water levels stabilize around 0.8 m-ss in summertime due to the set preferable *GWL* of 0.8 m-ss, the water levels fluctuate in wintertime due to alternating water retention and discharge. In general, water levels simulated with SWAP show more meteorological fluctuations compared to water levels in SDM, resulting in a KGE of 0.28 and a RMSE of 0.19 m. This is possibly due to the calculation procedure of percolation and capillary rise in the SDM. However, the magnitude of the water levels simulated by the SDM is comparable to those simulated by SWAP, which is important for the calculation of the head differences between groundwater and surface water due to subirrigation.

ET_{act} increases due to subirrigation as a consequence of higher *GWL*, due to capillary rise and higher soil moisture availability in the root zone, as simulated by both the SDM and SWAP. The annual ET_{act} ranged from 300 to 600 mm in both the SDM and SWAP simulations (Figure 5.2C), depending on annual meteorological conditions. No drought stress develops in the average and wet years 2013-2017 and 2021. In dry years (2018-2020, 2022), ET_{act} increases with roughly 40% due to subirrigation, although some drought stress

occurs (Figure 5.2A, C). Both KGE and RMSE values indicate acceptable model performances.

Larger head differences between *GWL* and H_{ditch} due to subirrigation increase ditch drainage and downward seepage (Figure 5.7). Water for subirrigation is abstracted from the surface water, lowering H_{ditch}, but increasing ditch drainage, which results in a return flow to the surface water. Thus, the net use of surface water for CDSI is reduced due to increased ditch drainage, a process captured by the SDM. Pipe infiltration shows an instable/peaky pattern in summertime due to interacting process of surface water use, subirrigation raising groundwater levels and resulting increased ditch drainage. Finally, the mass water balance values of all individual reservoirs are checked and are in an acceptable range.

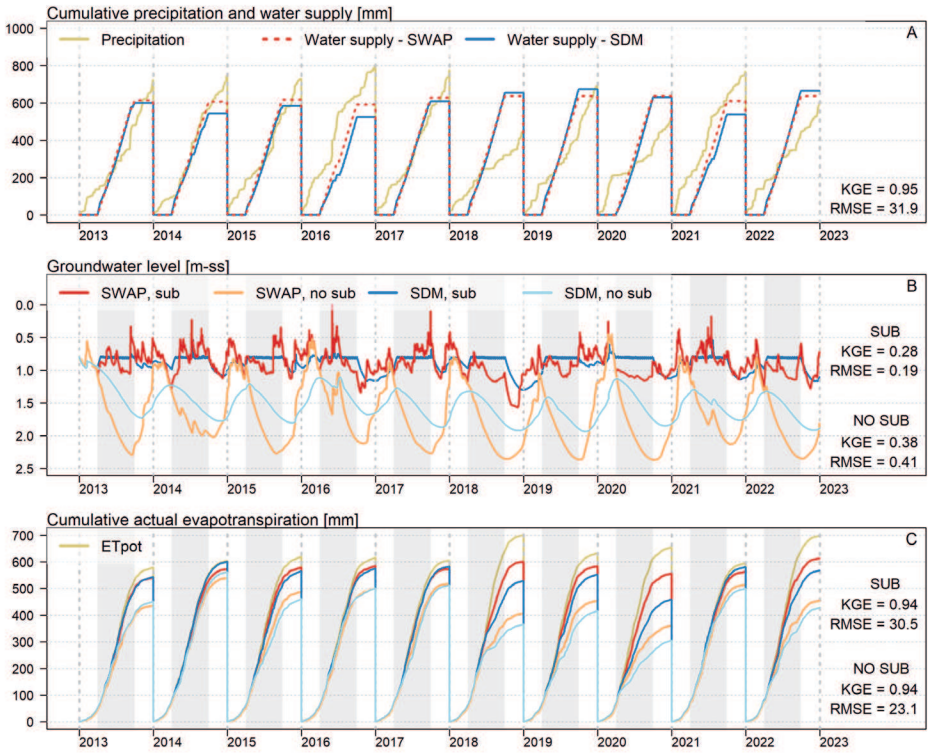


Figure 5.2: Overview of measured precipitation of the weather station Arcen and modelled subirrigation (A), groundwater level (B) and actual evapotranspiration (C). All components are simulated with both the lumped SDM and the agro-hydrological model SWAP, for situations with ('sub') and without ('no sub') subirrigation. The grey areas represent subirrigation periods. Statistics Kling-Gupta Efficiency (KGE) and Root Mean Squared Error (RMSE) are used to evaluate the performance of the SDM compared to the SWAP model. In conclusion, SDM captures the subirrigation patterns of the SWAP-model, which was calibrated against field measurements.

5.3.2 Hydrological consequences of CDSI upscaling using a lumped SDM

CDSI upscaling affects hydrologic fluxes, but is strongly limited by the regional water availability. Upscaling CDSI means that the regional water inflow remains the same while

the total amount of applied water for subirrigation increases as long as sufficient surface water is available (Figure 5.3A). Model results show that subirrigation increases from 600 mm/y to 700 mm/y when CDSI is upscaled from 1% to 25% of the total area. More water supply decreases H_{ditch} from 1 m-ss to 1.5 m-ss, resulting in increased ditch drainage. When CDSI is further upscaled to 50% and 80%, subirrigation decreases to 600 mm/y and 400 mm/y respectively. This is due to H_{ditch} reaching the minimum required level, which limits water availability for subirrigation. As a result of reduced subirrigation, ET_{act} decreases to 600 mm/y – 400 mm/y (Figure 5.3B). Groundwater levels are lowest and crop water stress is highest for higher percentages of upscaling (Figure 5.8), indicating that regional water supply is insufficient to meet the CDSI requirements. Water exits the system as ditch drainage and downward seepage (Figure 5.3C, D). Ditch drainage varies between 0.7 mm/d and 3 mm/d depending on the head differences between *GWL* and H_{ditch} (Figure 5.8). Due to the head difference, ditch drainage initially increases with higher percentages of upscaling, even though the required groundwater levels cannot be met, which is visible in the decrease in ET_{act}. However, beyond 50% upscaling, ditch drainage decreases because the *GWL* lowers. This is caused by limited water availability for supply, resulting in a small head difference between *GWL* and H_{ditch}. Nevertheless, head differences still increase due to low surface water levels, showing the feedbacks involved in regional CDSI implementation. At the highest values of upscaling, insufficient water is available for subirrigation due to overexploitation of surface water, leading to lower groundwater levels, and, consequently lower ET_{act}, ditch drainage and downward seepage.

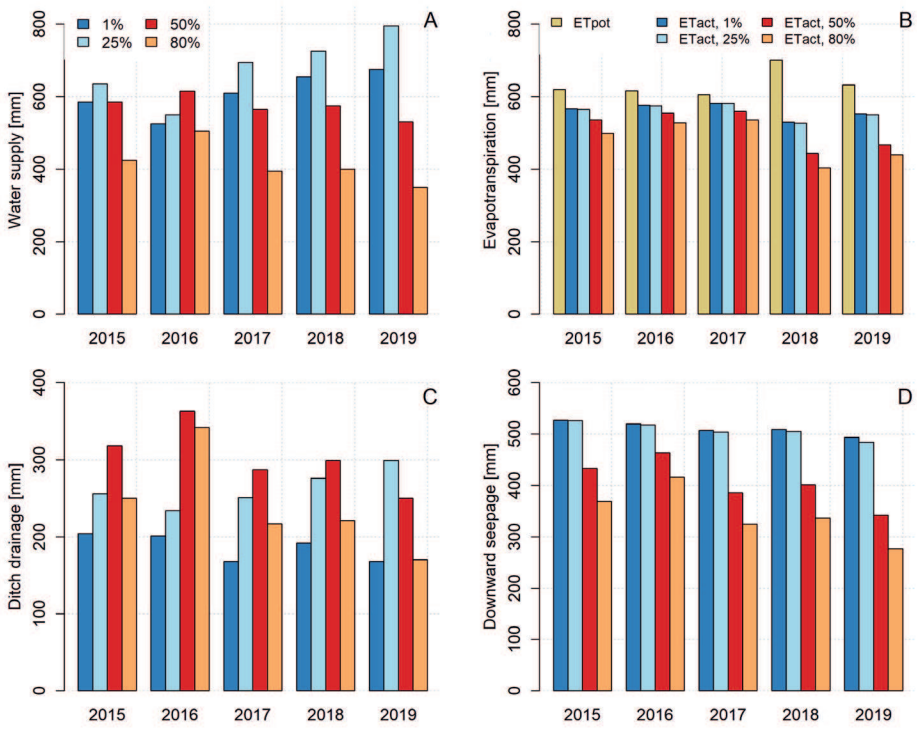


Figure 5.3: Overview of water supply (A), actual evapotranspiration (B), drainage to the ditch (C) and downward seepage (D) simulated with the lumped system dynamics model. All components are calculated using the model, including subirrigation ('sub'), for scenarios where 1%, 25%, 50% or 80% of the area applies subirrigation. In conclusion, CDSI upscaling affects almost all hydrological fluxes, but is strongly related to regional water availability.

Because meteorological conditions propagate through the entire soil water system, the need for subirrigation in the 50% scenario is lower in the wet year 2016 than in drier years. This also results in a higher H_{ditch} in 2016 compared to 2015 and 2017-2019 and a *GWL* close to the preferable *GWL* until August 2016. Furthermore, the lumped SDM is able to simulate the effects of heavy rainfall in June 2016 as a strong raise in GWL and Q_{ditch} occurs, resulting in a period of no subirrigation and more downward seepage (Figure 5.8). Conversely, in the dry years 2018-2019 insufficient surface water is available to raise the *GWL* to the preferable *GWL* for the 50% and 80% subirrigation scenario (Figure 5.8). As a result, ET_{act} decreases, drought stress develops and ditch drainage declines throughout the summer (Figure 5.3C, Figure 5.8). Thus, the SDM is able to simulate the consequences of meteorological conditions on the propagation and effectiveness of CDSI upscaling.

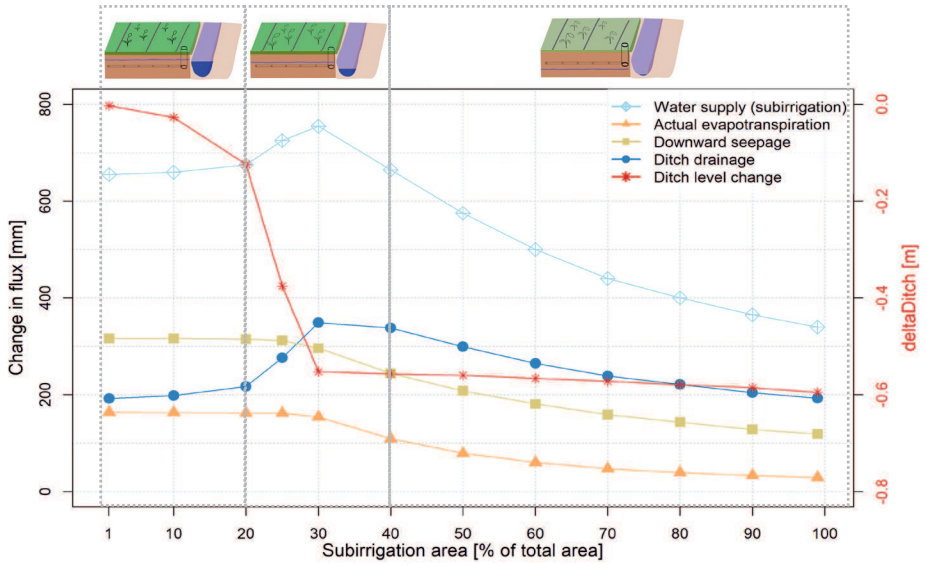


Figure 5.4: The increase in the hydrological fluxes water supply, actual evapotranspiration, downward seepage and ditch drainage based on SDM simulations (subirrigation minus no subirrigation) as well a change in ditch level (maximum minus minimum per simulation,'deltaDitch', right y-axis) are shown as function of the percentage of the total area applying subirrigation ('subirrigation area') for the year 2018. In conclusion, CDSI upscaling shows non-linear propagation in hydrological fluxes, in which three phases could be identified.

Upscaling of CDSI shows non-linear effects in hydrological fluxes, in which three distinct phases can be distinguished, demonstrated for 2018 (Figure 5.4). First, from 1% to 20% CDSI area, subirrigation and Q_{ditch} increase (with 30 mm and 31 mm respectively) while H_{ditch} slightly decreases (0.12 m) and ET_{act} and *DS* remain roughly the same. This means that sufficient surface water is available to upscale CDSI to 20%, with little impact on the regional surface water availability. Second, from 20% to 30% CDSI area, subirrigation and Q_{ditch} increase (70 mm and 140 mm respectively), while H_{ditch}, ET_{act} and *DS* decrease (0.42 m, 4 mm and 26 mm respectively). This means that sufficient water is available to upscale CDSI to 30%, but H_{ditch} drops sharply, which increases Q_{ditch}, causing an increase in the water demand for subirrigation to reach the desired *GWL*, further enhancing the impact on regional water availability. Third, from 30% to 99% CDSI area, Q_{subirri}, Q_{ditch}, ET_{act} and *DS* decrease (430 mm, 141 mm, 109 mm, 177 mm respectively), as surface water availability limits the amount of subirrigation. ET_{act} increase reduces with 80% between 30% and 99% area of CDSI to about 27 mm increase in ET_{act} compared to a situation without subirrigation, which makes subirrigation likely unbeneficial. When subirrigation would still be applied for this specific situation, this would not improve crop water availability and negatively impacts surface water level. In conclusion, three critical phases related to regional water availability determine the possibilities for CDSI upscaling. It is crucial to identify which phase the effects of upscaling correspond to: from Phase 1, with sufficient regional water availability; through Phase 2, a critical zone where water demand begins to limit regional availability; to Phase 3, where high water demand significantly impacts the regional water system and CDSI is no longer beneficial for the crop.

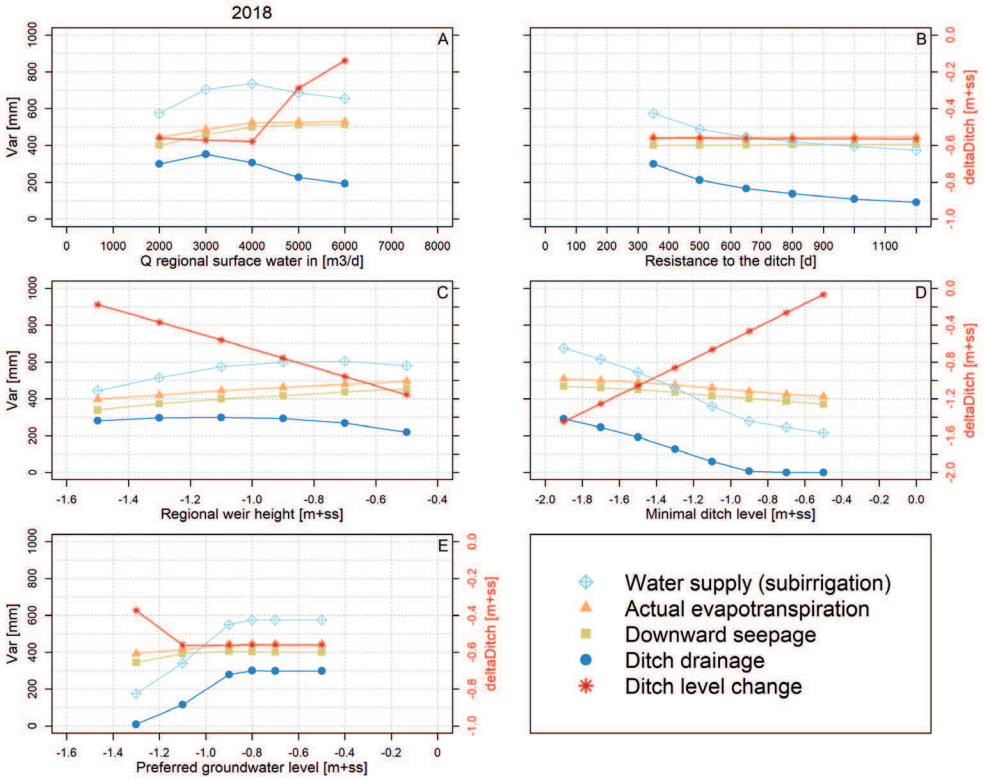


Figure 5.5: Simulated hydrological fluxes subirrigation, actual evapotranspiration, downward seepage and ditch drainage as well as change in ditch level (annual maximal minus minimum 'deltaDitch', right y-axis) as function of regional inflow of surface water (A), resistance to the ditch (B), regional weir height (C), minimal ditch level (D) and preferable groundwater level (E). All simulations assume that 50% of the total area applies subirrigation for 2018. Base input for all scenarios includes 2000 m^3/d surface water inflow, a weir height of 1.1 m-ss, minimal ditch level of 1.6 m-ss (with a weir height of 0.5 m-ss), a preferred GWL of 0.8 m-ss unless the respective variable was modified. In conclusion, limitations in regional water availability for CDSI upscaling to 50% depend strongly on geohydrological characteristics, local scale water management and regional water management.

Limitations imposed by the regional water availability strongly depend on geohydrological characteristics, field scale water management and regional water management. A key geohydrological characteristic is the drainage resistance towards the ditch, which also reflects the orientation of the CDSI fields: fields oriented perpendicular to the ditch have a higher drainage resistance than those parallel to it. Field water management is characterized by the preferable *GWL* for crop growth. Regional water management determines the inflow to the regional surface water, weir management and minimal required H_{ditch}. In general, measures to increase regional surface water availability, may provide more opportunities for CDSI upscaling and thus subirrigation, which raises the *GWL* and increases ET_{act}, *DS* and Q_{ditch} (Figure 5.5). Furthermore, a lower preferable *GWL* or higher drainage resistance to the ditch ensures that less water is needed to meet the preferable *GWL* and, as a result, more water remains regionally available (Figure 5.5). Therefore, the limitations of upscaling CDSI depend on both the regional water management by the water authorities and the water management by the farmer.

5.4 Discussion

CDSI is increasingly used to improve field-scale water management in agriculture, but it also increases pressure on regional water availability, which is managed by regional water authorities. Applying field scale hydrological measures in agriculture requires in-depth understanding of the regional water availability and demand. The SDM approach in this chapter provides insight into i) the net impact of CDSI upscaling on hydrological fluxes and water levels, ii) the impact of water management by farmers, and iii) the impact of water management by water management authorities. The SDM was built with two main goals: i) to serve as a simple but comprehensive decision support tool for policymakers, providing quick insights into the propagation of CDSI upscaling, and ii) to act as a tool that bridges the knowledge gap between farmers and policymakers. To achieve these goals, it was important that the model could operate across different time scales and include the relevant subsystems: i) regional water inflow managed by water authorities, ii) subirrigation applied by farmers and, iii) interactions between groundwater levels, surface water levels and the unsaturated zone. Combining field scale expertise with regional analysis can contribute to a shared understanding of responsible CDSI upscaling.

A major challenge in the Netherlands is the distribution of water through the regional water system, that supports both nature and the anthropogenic water demands of various sectors, which often compete for similar water sources. Hydrological consequences of CDSI at one single field cannot be extrapolated linearly to a larger area, because the hydrological consequences of upscaling CDSI involve non-linear feedbacks. The SDM approach is able to capture and visualize these feedbacks. Thus, using an SDM, water management authorities could obtain insight into the balance between water availability and the potential for upscaling CDSI within a region. This can be particularly useful in the early stages of strategic area planning, when optional measures are being explored. In Figure 5.4, insufficient water is available to implement CDSI in more than 40% of the area. Depending on site suitability and regional water availability for subirrigation, controlled drainage could be converted to CDSI, or it may be decided not to support the implementation of CDSI to mitigate water stress.

An SDM approach is a simple but comprehensive tool that uses concise equations to approximate the results of a more complex model (Khan et al., 2009). This comes with both strengths and limitations. The lumped SDM is designed such that it is transparent, and makes it relatively easy to understand the system and impacts of management scenarios. Subsystems (and equations) can easily be added. However, it should always be considered whether adding complexity contributes to improved understanding (Wagener et al., 2001).

The main strengths of the developed SDM are the interactions between the important CDSI subsystems. First, the net effect of subirrigation on surface water levels is key in CDSI upscaling. Second, while the interaction between the *GWL* and unsaturated zone by CDSI is crucial for understanding crop water availability, it has been insufficiently addresses in other literature. This study contributes to the literature by including this interaction into an SDM setup. Conversely, a limitation of the SDM could be that a lumped model provides

integral results in the order of magnitude of hydrological fluxes and water levels, rather than spatially explicit impacts at specific fields. Second, the SDM simplifies soil water flow by assuming instantaneous water redistribution in its reservoirs, whereas numerical models such as SWAP solve the Richards equation to simulate gradual vertical flow in the unsaturated zone. This may lead to an overestimation of upward and downward water flow rates in the unsaturated soil, resulting in more stable groundwater levels rather than fluctuations due to precipitation and evapotranspiration (Figure 5.2). However, the simulated *GWL* using the SDM shows a RMSE of 0.19 m compared to SWAP and, given that the magnitude of water levels and hydrological fluxes is key in this study, the model appears to be a valid approach. Third, given the lack of studies in which CDSI is upscaled, we initiated this study with a base SDM representing a single field (1% of the area) to assess the plausibility of using an SDM. The outcomes of the SDM were compared with the results of the agro-hydrological model SWAP, which was calibrated against field measurements. CDSI was then upscaled, assuming uniform soil and crop characteristics across the region. De Wit et al. (2024b) shows that increasing the rooting depth from 30 to 50 cm reduces the water demand for subirrigation. For this study, it implies that due to the limited rooting depth the subirrigation demand might be slightly overestimated. Although the aim of this study was to present a methodology to efficiently explore the feasibility of CDSI upscaling, in further applications of the SDM varying soil or crop characteristics can be included.

5.5 Conclusion

Controlled drainage with subirrigation is a viable measure to recharge, retain and discharge water at the field scale (De Wit et al., 2024c). CDSI upscaling and consequently regional implementation requires consideration of non-linear feedbacks and hydrological effects. Therefore, field scale effects cannot be translated linearly into impacts on regional scale water management. To address this, a lumped model was built for CDSI upscaling that i) captures interactions between surface water and groundwater, and between the unsaturated zone and groundwater, ii) identifies negative and positive feedbacks between hydrological components as water supply for CDSI, evapotranspiration, downward seepage and ditch drainage, and iii) simulates efficiently to evaluate multiple scenarios, while providing insight into CDSI upscaling effects and supporting initial decision making.

CDSI upscaling showed non-linear propagation in hydrological fluxes in which three phases can be identified: 1) sufficient surface water is available for CDSI upscaling, with minimal impact on regional surface water availability, 2) sufficient water is available for upscaling, but the surface water level drops sharply, increasing the impact on regional water availability and 3) surface water availability becomes a limiting factor for subirrigation, restricting crop water availability and putting a large pressure on regional surface water levels. Furthermore, limitations by regional water availability strongly depend on geohydrological characteristics and regional water management, meaning that the effects of CDSI upscaling depend on both the regional strategies by water management authorities and practices by farmers. Understanding the consequences of upscaling CDSI is important for water management authorities in the strategic planning of regional development.

An SDM approach may serve as discussion support tool and can be applied in the initial design of CDSI upscaling to estimate the resulting regional water demand. However, a detailed understanding of CDSI systems, based on field experiments or modelling is essential to make informed decisions about the required level of complexity in SDM. Although the model has been parameterized for a CDSI system within the Dutch context, its process-based structure allows for adjustment of input parameters as weather, crop types, soil characteristics and water management strategies. Therefore, the SDM could be applied to other regions suitable for CDSI, particularly groundwater-dependent systems such as delta areas. The SDM approach could support in the design of CDSI upscaling across a range of geohydrological settings. In conclusion, while CDSI can contribute to regional water management strategies, CDSI upscaling shows non-linear propagation in hydrological fluxes. An SDM could support water management authorities in understanding how field scale application of CDSI propagates through the regional water system, and in informing decision makers by assessing to what extent CDSI upscaling by farmers can be facilitated.

5.6 Appendix

5.6.1 Appendix: detailed description SDM set-up

The general setup of the system dynamics model (SDM) for regional evaluation of upscaling of CDSI contains the key elements and hydrological fluxes affected by a CDSI system embedded in a regional context (Figure 5.6). In general, a CDSI system consists of a control pit where external water (from a ditch) for subirrigation is applied. The control pit is connected to a collector pipe, which is then connected to the infiltration pipes perpendicular to the collector pipe. Water flows through the drains and enters the groundwater through the perforated holes of the drain. Soil moisture reaches the rooting zone of plants through capillary rise from the groundwater. The SDM is programmed in Vensim (version: Vensim PLE Plus 9.0.1 x64). System components are described as state variables ('stocks' or reservoirs) connected with hydrological fluxes ('flows'). Auxiliary variables are connected through 'connectors or arrows' (e.g. wilting point, drain spacing). The detailed calculations and description of the SDM are described below as well as the input data based on a field experiment that are used as starting point (De Wit et al., 2024c).

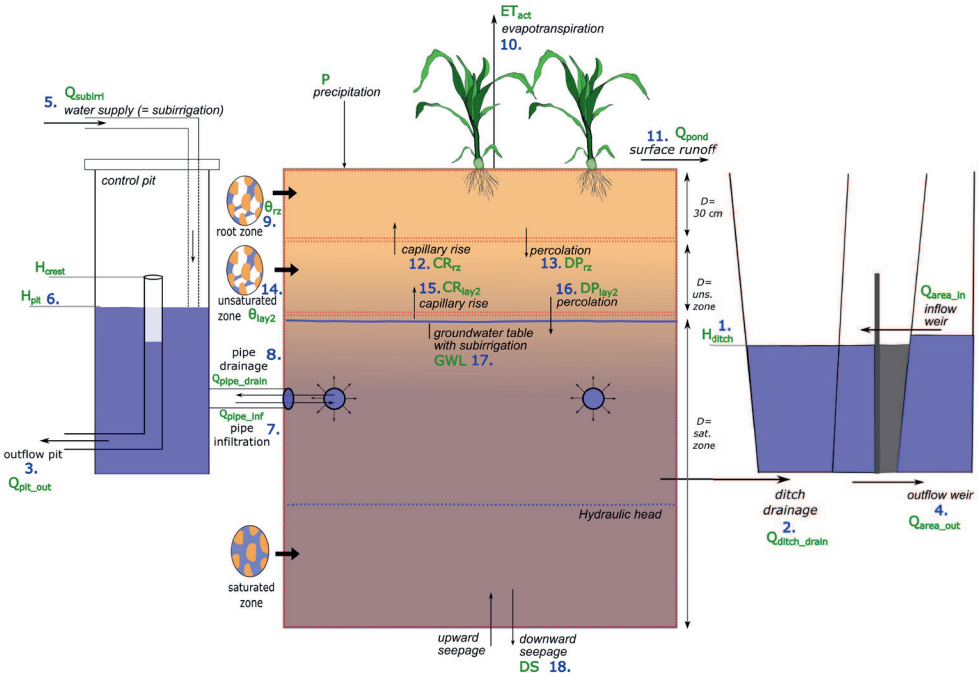


Figure 5.6: Overview processes in SDM (black) with the corresponding numbers of the formulas in this appendix (blue) and corresponding abbreviations (green).

5.6.1.1 Regional approach: weir and ditch

The modelled regional area is primarily a water supply area that is intensively managed with water distributed via ditches. Outflow occurs when the ditch level exceeds the weir level. Surface water level (H_{ditch}) (m-ss) is described as:

$$H_{\mathrm{ditch,t}} = H_{\mathrm{ditch,t-1}} + \frac{Q_{\mathrm{ditch,t}} + Q_{\mathrm{area_in,t}} + Q_{\mathrm{pit_out,t}} - Q_{\mathrm{area_out,t}} - Q_{\mathrm{subirri,t}}}{A_{\mathrm{ditch}}} \quad [1]$$

where $H_{\mathrm{ditch,t-1}}$ is ditch level at timestep t-1 (m), Q_{ditch} is ditch drainage (m^3), $Q_{\mathrm{area_in}}$ is regional inflow (m^3), $Q_{\mathrm{pit_out}}$ is water drained from the pit to the ditch (m^3), $Q_{\mathrm{area_out}}$ is regional outflow (m^3), Q_{subirri} is water abstracted for subirrigation (m^3), A_{ditch} is ditch area (m^2). The fluxes are calculated sequentially as:

- $Q_{\mathrm{ditch,t}} = \frac{GWL - H_{\mathrm{ditch,t}}}{c_{\mathrm{ditch}}} * A_{\mathrm{sub}}$ $GWL > H_{\mathrm{ditch}}$ [2]
- $Q_{\mathrm{pit_out,t}} = (H_{\mathrm{pit,t}} - H_{\mathrm{crest,t}}) * A_{\mathrm{pit}}$ $H_{\mathrm{pit}} > H_{\mathrm{crest}}$ [3]
- $Q_{\mathrm{area_out,t}} = 1.7 * m * b * hs^{\frac{3}{2}} * 86400$ $H_{\mathrm{ditch}} > H_{\mathrm{weir}}$ [4]
- $Q_{\mathrm{subirri,t}} = V_{\mathrm{subirri,t}} * A_{\mathrm{sub}}$ $GWL < GWL_{\mathrm{pref}}$ & $H_{\mathrm{ditch}} > H_{\mathrm{ditch.min}}$ [5]

where GWL is the groundwater level (m-ss), c_{ditch} is ditch drainage and infiltration resistance (d), A_{sub} is total area with CDSI fields (m^2), H_{pit} is water level in the pit, H_{crest} is crest height, A_{pit} represents the total area in the underground system where subirrigation is applied, including the pit, pipes and soil around the pipes. A_{pit} is estimated as $A_{\mathrm{pit}} = 0.19 * A_{\mathrm{sub}}$ (m^2), where A_{sub} is the area with CDSI fields (m^2). The factor 0.19 was estimated based on manual calibration of the simulated H_{pit} to the measured H_{pit}. m is weir shape, b is weir width, hs is overflow height calculated as $H_{\mathrm{ditch}} - H_{\mathrm{weir}}$, where H_{weir} is weir height (CultuurtechnischeVereniging, 1988). V_{subirri} is subirrigation (m). Q_{subirri} occurred from 1st April to 30th September and only when surface water is available as source for subirrigation.

5.6.1.2 CDSI systems: control pit

The control pit is key in the CDSI setup because it determines the drainage and infiltration level of a field. Pit water level (H_{pit}) is estimated as:

$$H_{\mathrm{pit,t}} = H_{\mathrm{pit,t-1}} + \frac{Q_{\mathrm{pipe_drain,t}} + Q_{\mathrm{subirri,t}} - Q_{\mathrm{pit_out,t}} - Q_{\mathrm{pipe_inf,t}}}{A_{\mathrm{pit}}} \quad [6]$$

where $H_{\mathrm{pit,t-1}}$ is level in the control pit at timestep t-1 (m), $Q_{\mathrm{pipe_drain}}$ is pipe drainage (m^3), Q_{subirri} is water supply (m^3), $Q_{\mathrm{pit_out}}$ is pit drainage (m^3), $Q_{\mathrm{pipe_inf}}$ is pipe infiltration (m^3), A_{pit} represents the total area in the underground system where subirrigation is applied, including the pit, pipes and soil around the pipes. A_{pit} is estimated as $A_{\mathrm{pit}} = 0.19 * A_{\mathrm{sub}}$ (m^2), where A_{sub} is the area with CDSI fields (m^2). The factor 0.19 was estimated based on manual calibration of the simulated H_{pit} to the measured pit levels in the field experiment. The fluxes are calculated sequentially as:

- $Q_{\mathrm{pipe_inf}} = \frac{H_{\mathrm{pit,t}} - GWL_{\mathrm{t}}}{c_{\mathrm{pipes}}} * A_{\mathrm{sub}}$ $GWL < H_{\mathrm{pit}}$ [7]

- $Q_{\text{pipe_drain,t}} = \frac{GWL_{\text{t}} - H_{\text{pit,t}}}{c_{\text{pipes}}} * A_{\text{sub}}$ $GWL > H_{\text{pit}}$ [8]

where c_{pipes} (d) is pipe drainage and infiltration resistance. Furthermore, H_{pit} is controlled via the crest height (H_{crest}). The control pit retains groundwater when $H_{\text{pit}} < H_{\text{crest}}$ & $Q_{\text{subirri}} = 0$, recharges groundwater when $H_{\text{pit}} < H_{\text{crest}}$ & $Q_{\text{subirri}} > 0$, and discharges water when $H_{\text{pit}} > H_{\text{crest}}$.

5.6.1.3 Rooting zone

The soil water system was split into the rooting zone, the second layer of the unsaturated zone and the saturated zone. The soil moisture content in the rooting zone (θ_{rz}) (m^3/m^3) is estimated as:

$$\theta_{\text{rz,t}} = \theta_{\text{rz,t-1}} + \frac{P_{\text{t}} - ET_{\text{act,t}} + CR_{\text{rz,t}} - DP_{\text{rz,t}} - Q_{\text{pond,t}}}{Dr_{\text{rz}} * A_{\text{sub}}} \quad \theta_{\text{wp}} < \theta_{\text{rz}} < \theta_{\text{sat}} \text{ [9]}$$

where $\theta_{\text{rz,t-1}}$ is the SMC in the rooting zone at timestep t-1 (m^3/m^3), P is precipitation (m^3), CR_{rz} is capillary rise from the second layer to the rooting zone (m^3), ET_{act} is actual evapotranspiration (m^3), DP_{rz} is deep percolation from the rooting zone to the second layer (m^3), Q_{pond} is ponding layer that disappears as runoff (m^3), Dr_{rz} is the rooting zone depth (m). Furthermore, ET_{ref} was multiplied by a crop factor to calculate potential evapotranspiration (ET_{pot}). Next, ET_{pot} was multiplied by a reduction factor for reduced root water uptake due to water limitation, to calculate ET_{act}. As a linear relationship is assumed between relative transpiration and relative crop yield (De Wit, 1958), $ET_{\text{act}} < ET_{\text{pot}}$ indicates that crop water demand cannot be met and thus drought stress occurs.

- $ET_{\text{pot,t}} = ET_{\text{ref,t}} * CF$ [10a]
- $TAW_{\text{t}} = (\theta_{\text{fc,t}} - \theta_{\text{wp,t}}) * Dr_{\text{rz,t}} * A_{\text{sub}}$ [10b]
- $ET_{\text{redfact,t}} = \frac{\theta_{\text{rz,t}} * A_{\text{sub}} * Dr_{\text{rz,t}}}{TAW_t * p_{\text{stress}}}$ $0 < ET_{\text{redfact}} < 1$ [10c]
- $ET_{\text{act,t}} = ET_{\text{pot,t}} * ET_{\text{redfact,t}}$ [10d]

where CF is crop factor (-), TAW total available soil water (m^3), θ_{fc} is SMC by field capacity, θ_{wp} is SMC by wilting point, p_{stress} is an average fraction. $TAW * p_{\text{stress}}$ indicates the amount of water that can be depleted from the root zone before moisture stress occurred, also known as readily available water (RAW) (Allen et al., 1998). The other variables are described as:

- $Q_{\text{pond,t}} = (\theta_{\text{rz,t}} - \theta_{\text{sat}}) * Dr_{\text{rz}} * A_{\text{sub}}$ $\theta_{\text{rz}} > \theta_{\text{sat}}$ [11]
- $CR_{\text{rz,t}} = \exp\left(\frac{ln(GWL_{\text{t}}) - a}{b}\right) * A_{\text{sub}}$ $\theta_{\text{wp}} < \theta_{\text{rz}} < \theta_{\text{sat}}$ [12a]
  with $a = -1.4936 + 0.2146 * \ln(k_{\text{s}})$, $b = -0.03112 - 10^{-5} * k_{\text{s}}$ [12b]
- $DP_{\text{rz,t}} = k(\theta) = k_{\text{s}} * S_{\text{e}}^{\lambda} * \left[1 - \left(1 - S_{\text{e}}^{\frac{1}{m}}\right)^{m}\right]^2 * A_{\text{sub}}$ $\theta_{\text{wp}} < \theta_{\text{rz}} < \theta_{\text{sat}}$ [13a]
  with $S_{\text{e}} = \frac{\theta_{\text{rz,t}} - \theta_{\text{res}}}{\theta_{\text{sat}} - \theta_{\text{res}}}$ and $m = 1 - \frac{1}{n}$ [13b]

Q_{pond} is ponding layer (m^3), θ_{sat} is saturated water content (m^3/m^3), CR_{rz} is capillary rise (m^3) estimated by considering the soil type and the hydraulic characteristics according to AquaCrop (Raes et al., 2023), parameters a and b represent the textural soil class (Janssens, 2006), k_{s} is saturated hydraulic conductivity. DP_{rz} is deep percolation (m^3) assumed as free drainage and estimated as a function of saturated permeability and relative saturation according to the Warrilow model (Warrilow, 1986), θ_{res} is residual water content (m^3/m^3), λ is exponent in hydraulic conductivity function (-) , n is shape parameter (-).

5.6.1.4 Second unsaturated zone layer

The second layer of the unsaturated soil is between the rooting zone and GWL. Therefore, the depth of this layer (Dr_{lay2}) varies depending on the GWL. SMC in the second layer (θ_{lay2}) is estimated as:

$$\theta_{\mathrm{lay2,t}} = \theta_{\mathrm{lay2,t-1}} + \frac{\mathrm{CR_{lay2,t}} - \mathrm{CR_{rz,t}} + \mathrm{DP_{rz,t}} - DP_{\mathrm{lay2,t}}}{Dr_{\mathrm{lay2,t}} * A_{\mathrm{sub}}} \qquad \theta_{\mathrm{wp}} < \theta_{\mathrm{lay2}} < \theta_{\mathrm{sat}} \quad [14]$$

where $\theta_{\mathrm{lay2,t-1}}$ is the SMC in the second layer of the unsaturated soil at timestep t-1 (m^3/m^3). Water leaves the upper boundary of the second layer as CR_{rz} and enters the second layer as DP_{rz}. Water exits the lower boundary as DP_{lay2} and enters as CR_{lay2}. DP_{lay2} and CR_{lay2} were calculated as follows, where the parameters are similar to formula 12 and 13.

- $CR_{\mathrm{lay2,t}} = \exp\left(\frac{ln(GWL_{\mathrm{t}}) - a}{b}\right) * A_{\mathrm{sub}} \qquad \theta_{\mathrm{wp}} < \theta_{\mathrm{lay2}} < \theta_{\mathrm{sat}}$ [15]
- $DP_{\mathrm{lay2,t}} = k(\theta) = k_{\mathrm{s}} * S_{\mathrm{e}}^{\lambda} * \left[1 - \left(1 - S_{\mathrm{e}}^{\frac{1}{m}}\right)^{m}\right]^2 * A_{\mathrm{sub}} \quad \theta_{\mathrm{wp}} < \theta_{\mathrm{lay2}} < \theta_{\mathrm{sat}}$ [16a]

  with $S_{\mathrm{e}} = \frac{\theta_{\mathrm{lay2,t}} - \theta_{\mathrm{res}}}{\theta_{\mathrm{sat}} - \theta_{\mathrm{res}}}$ and $m = 1 - \frac{1}{n}$ [16b]

5.6.1.5 Saturated zone

The saturated zone is between the second layer of the unsaturated zone and 5 m depth (total depth of the soil column). The upper boundary of the saturated zone represents the GWL, estimated by

$$GWL_{\mathrm{t}} = GWL_{\mathrm{t-1}} + \frac{DP_{\mathrm{lay2,t}} + Q_{\mathrm{pipe_inf,t}} - CR_{\mathrm{lay2,t}} - Q_{\mathrm{ditch_drain,t}} - Q_{\mathrm{pipe_drain,t}} + DS_{\mathrm{t}}}{A_{\mathrm{sub}}} * \frac{1}{S} \quad [17]$$

where $GWL_{\mathrm{t-1}}$ is the GWL at timestep t-1 (m-ss), S is the storage coefficient (-) and DS is seepage (m^3). DS is estimated as:

- $DS = \frac{H_{\mathrm{aquifer}} - GWL}{c_{\mathrm{subsoil}}} * A_{\mathrm{sub}}$ [18]

where H_{aquifer} is the average hydraulic head of the deep aquifer, which was estimated using a sine function, c_{subsoil} is the system resistance to downward seepage.

5.6.2 Input SDM

Table 5.1: input for the SDM.

Abbreviation	Unit	Value	Reference
A_{ditch}	m^2	259,200	Water management authority Limburg
A_{pit}	m^2	0.19*A_{sub}	
A_{sub}	m^2	Scenario dependent	Water management authority Limburg
b	m	1.95	CultuurtechnischeVereniging (1988)
c_{ditch}	d	350	De Wit et al. (2024c)
c_{pipes}	d	10.2	Van der Gaast (2006)
$c_{subsoil}$	d	800	De Wit et al. (2024c)
CR: α and b	-	'sandy soils'	Janssens (2006)
CF	-	1	Allen et al. (1998)
DR_{rz}	m	0.30	Estimated from field experiments (De Wit et al., 2024c)
GWL_{pref}	m-ss	0.80	Estimated from field experiments (De Wit et al., 2024c)
$GWL_{t=0}$	m-ss	0.80	Estimated from field experiments (De Wit et al., 2024c)
H_{crest}	m-ss	0.52 (1st Oct – 31st March) 0.50 (1st Apr - 30th Sep)	Estimated from field experiments (De Wit et al., 2024c)
$H_{ditch,min}$	m-ss	1.6	Estimated from field experiments (De Wit et al., 2024c)
$H_{ditch,t=0}$	m-ss	1.1	Estimated from field experiments (De Wit et al., 2024c)
$H_{pit,t=0}$	m-ss	0.8	Estimated from field experiments (De Wit et al., 2024c)
H_{weir}	m-ss	1.1	Estimated from field experiments (De Wit et al., 2024c)
K_s	m/d	0.2276	Heinen et al. (2020)
λ	-	2.44	Heinen et al. (2020)
m	-	0.87	CultuurtechnischeVereniging (1988)
n	-	1.524	Heinen et al. (2020)
p_{stress}	-	0.6 (Grazing Pasture/ Rye Grass hay)	Allen et al. (1998)
S	-	0.10	CultuurtechnischeVereniging (1988)
Sine function $H_{aquifer}$		frequency = 1/365 (-) amplitude = 0.60 m phase = -202 d starting point = 30 d	De Wit et al. (2024c)
θ_{fc}	m^3/m^3	0.27	Allen et al. (1998) (h= -100 cm)

$\boldsymbol{\theta_{lay2,t=0}}$	m^3/m^3	0.23	Estimated from field experiments (De Wit et al., 2024c)
$\boldsymbol{\theta_{res}}$	m^3/m^3	0.02	Heinen et al. (2020)
$\boldsymbol{\theta_{rz,t=0}}$	m^3/m^3	0.23	Estimated from field experiments (De Wit et al., 2024c)
$\boldsymbol{\theta_{sat}}$	m^3/m^3	0.387	Olsthoorn (1977) and Heinen et al. (2020).
$\boldsymbol{\theta_{wp}}$	m^3/m^3	0.04	Heinen et al. (2020) (h = -16,000 cm).
$\boldsymbol{Q_{area_in}}$	m^3/d	2000	Water management authority Limburg
$\boldsymbol{V_{subirri}}$	m	0.005	De Wit et al. (2024c)
Weather ($\boldsymbol{P}$ and $\boldsymbol{ET_{ref}}$)	m	Weather station Arcen	Royal Netherlands Meteorological Institute

5.6.3 *Appendix: detailed results*

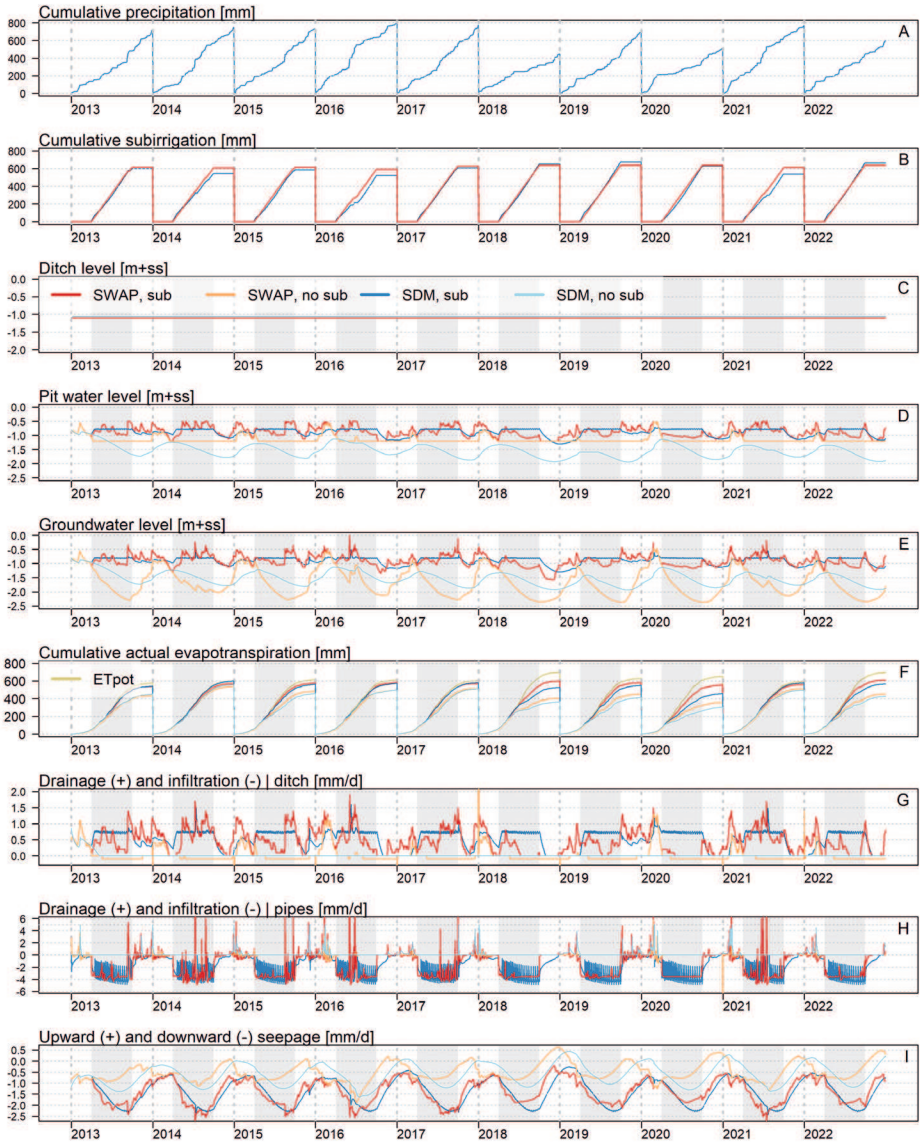


Figure 5.7: Overview of measured cumulative precipitation of the KNMI station Arcen (A), cumulative subirrigation (B), ditch level (C), pit water level (D), groundwater level (E), cumulative actual evapotranspiration (F), drainage and infiltration of the ditch (G), drainage and infiltration of the pipes (H) and upward and downward seepage (I). All components are simulated with both the lumped SDM and the agro-hydrological model SWAP, for situations with ('sub') and without ('no sub') subirrigation. The grey areas represent subirrigation periods. In conclusion, SDM captures subirrigation patterns of the SWAP-model, which was calibrated against field measurements.

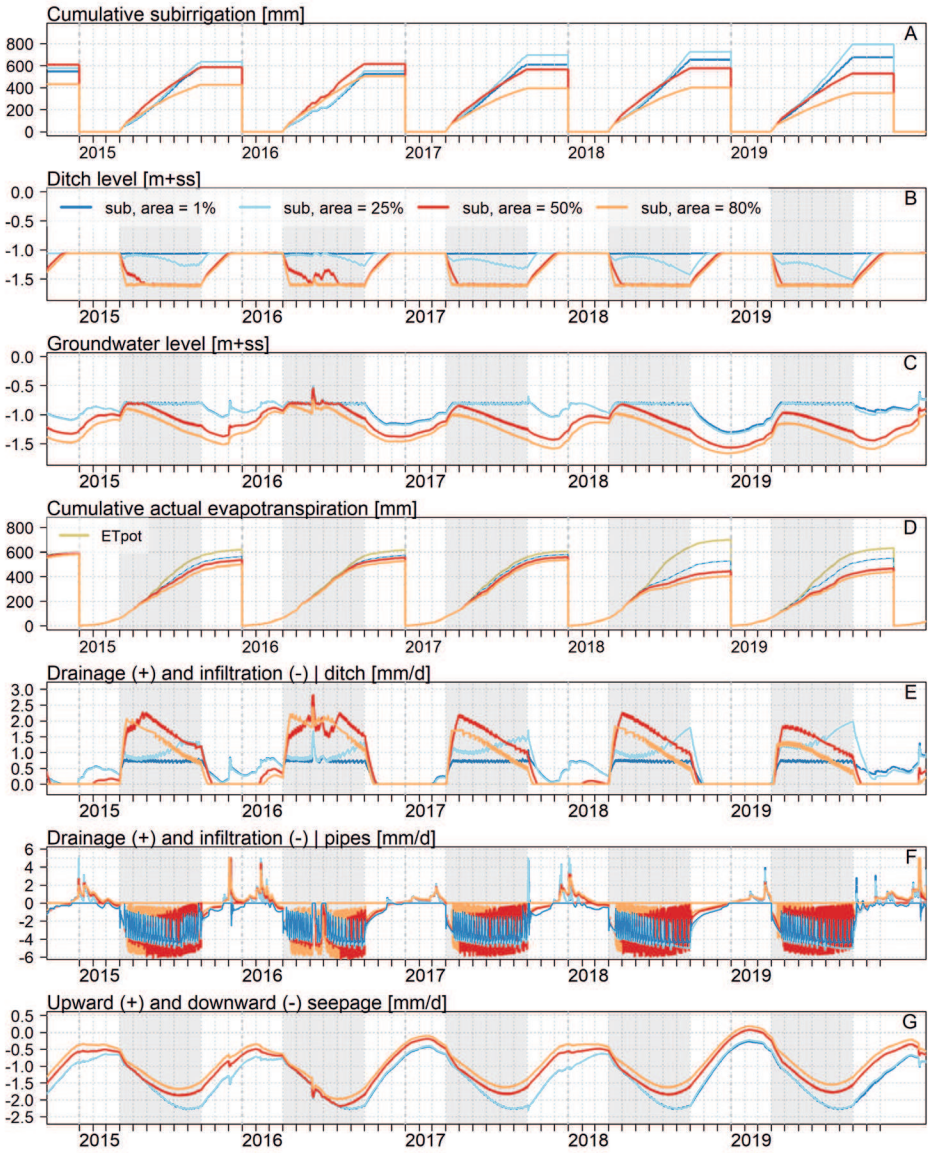


Figure 5.8: Overview of cumulative subirrigation (A), ditch level (B), groundwater level (C), cumulative actual evapotranspiration (D), drainage and infiltration to/from the ditch (E), drainage and infiltration of the pipes (F) and upward and downward seepage (I). All components are calculated using the model, including subirrigation ('sub'), for scenarios where 1%, 25%, 50% or 80% of the area applies subirrigation ('area = X %'). In conclusion, CDSI upscaling affects almost all hydrological fluxes, but is strongly related to regional water availability.

6

CHAPTER 6

SYNTHESIS

"IF YOUR DREAMS DO NOT SCARE YOU, THEY ARE NOT BIG ENOUGH"
ELLEN JOHNSON SIRLEAF

6 Synthesis

The aim of this thesis is to identify the hydrological opportunities and limitations for implementing controlled drainage with subirrigation at local and regional scales in the Pleistocene uplands of the Netherlands. In the previous chapters, a detailed analysis is provided from the development of drainage systems over the past century to the hydrological consequences of implementing CDSI systems at the local and the regional scale. Although CDSI is implemented at local scale, its hydrological impacts may influence the broader regional system. In this synthesis, I will discuss the main scientific findings of this thesis in section 6.1. The research underlying this thesis was originally motivated from a shared need from Dutch water management authorities and practitioners (farmers) to identify measures for a climate robust water system. Therefore, section 6.2 describes how CDSI could fit in a climate robust water system in the Netherlands translated to nine requirements to be considered (Figure 6.1), followed by insights from associated research not covered in this thesis and open research challenges. Finally, section 6.3 outlines how science can be translated from science to practice and society (section 6.3).

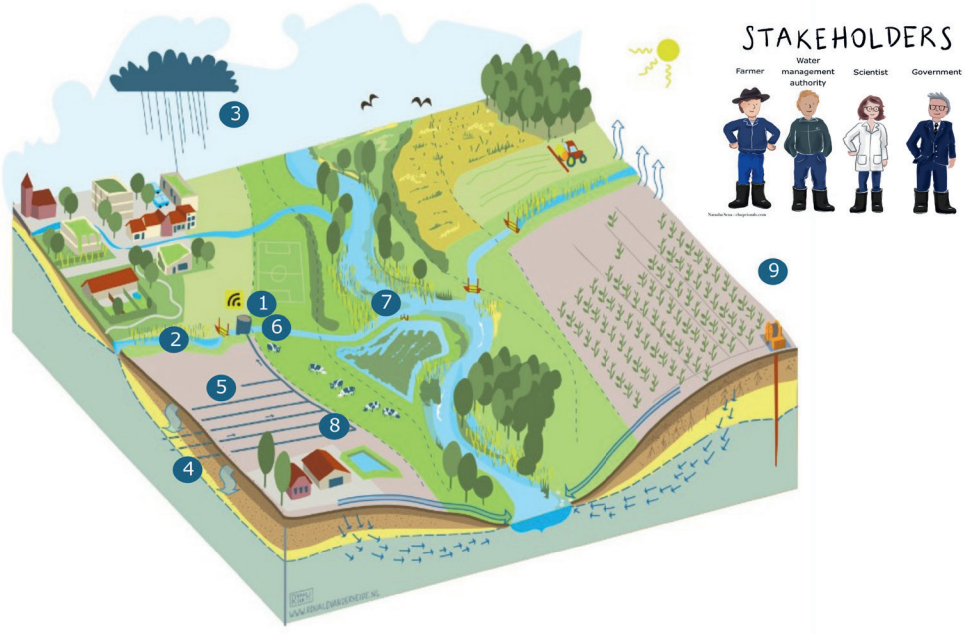


Figure 6.1: Overview of investigated aspects for implementing CDSI in this thesis: CDSI pit management (1), surface water management (2), meteorological characteristics (3), geohydrological characteristics (4), crop characteristics (5), source of water – local (6), source of water – regional (7), management and maintenance (8), stakeholders (9). Figure is adapted from www.stowa.nl/lumbricus.

6.1 Hydrological opportunities and limitations of CDSI

Sufficient fresh water is needed for nature and water dependent sectors such as agriculture, drinking water and industry. However, climate change, weather extremes, economic growth, urbanization, land subsidence and increased food production, among other factors, make it increasingly complex to guarantee sufficient fresh water for all sectors. The range of weather extremes from extremely dry to extremely wet is expected to increase and weather extremes are expected to occur more frequently. However, in many areas the water system is not designed to anticipate both weather extremes and to cope with the imbalance in water demand and water supply. Controlled drainage with subirrigation (CDSI) systems could be a viable measure to i) discharge, ii) retain, and iii) recharge water in agricultural fields. Therefore, the main research question of this thesis was:

What are the hydrological opportunities and limitations for implementing controlled drainage with subirrigation at local and regional scales in the Pleistocene uplands of the Netherlands?

The hydrological opportunities and limitations for implementing CDSI at local and regional scales in the Dutch Pleistocene uplands strongly depend on the local geohydrological characteristics. The results of this thesis are based on a combination of literature review, field experiments, agro-hydrological field scale modeling and a lumped system dynamics model for regional upscaling. Although the methods are tailored to the field pilots in the Netherlands, the setups are generally applicable, allowing to extend the analysis to other regions. In order to facilitate broader application, I have defined nine requirements that might be considered when converting traditional drainage systems or implementing new drainage systems (Figure 6.1, Figure 6.2). The requirements contribute to i) the design of CDSI systems for a range of geohydrological settings including quantification of required water supply rates for different CDSI management strategies, crop characteristics and meteorological conditions, ii) understand the local hydrological consequences of CDSI, iii) support water management authorities to understand how effects of field scale application of CDSI propagate through the regional water system, and iv) support the process of decision-making by determining to what extent upscaling of CDSI by farmers can be facilitated. Part of the requirements are based on the reflection on the sub-research of this thesis, described in the next paragraphs.

How have subsurface drainage systems developed in the 20th century including the corresponding drainage strategies and the consequences for the groundwater and surface water system?

Drainage systems developed over time in the Netherlands, occurring parallel to the structurally declining groundwater levels: from focus on drainage (conventional systems), to drainage and retention (controlled drainage systems) to drainage, retention and recharge (CDSI systems). Literature clearly shows that changes in drainage systems are mainly triggered by desiccation and land use changes as consequences of social, economic

and climate changes. However, the main Dutch water management system still has a primary focus on discharging water. Subsurface drainage systems could be converted to CDSI systems to focus more on discharge water to avoid flooding or waterlogging, retain water when possible and supply water when needed. However, CDSI could significantly alter water balance components. International literature showed that infiltration ranges between approximately 250 – 1500 mm/ 180 days. The *GWL* typically raised by a maximum of 30 – 40 cm and yield increased by a maximum of 64%. As conclusion, from literature follows that subirrigation raises the groundwater level and improves soil moisture conditions for crop growth. Literature also indicates that the supplied water could leave the system as drainage to ditches and downward seepage.

What are the hydrological consequences of subirrigation and how can these consequences be simulated using a field scale agro-hydrological model?

This paragraph explains how subirrigation affects water balance fluxes based on field data and modelling. CDSI contributes positively to operational groundwater level management for agricultural crop production at field scale. However, CDSI also alters the hydrological fluxes significantly. Measurements on four field experiments show that water supply ranged between roughly 500 to 1,000 mm and that CDSI systems are able to raise the groundwater level such that soil water availability for crops increases. Additional simulations with the SWAP model for field site A, as example, show that in a very dry year, actual plant transpiration increases with roughly 120 mm (= 41% increase) due to CDSI. However, this 120 mm is roughly only 16% of the supplied water. The other part of the supplied water mainly leaves the system as ditch and pipe drainage (34%) and downward seepage (35%). For meteorologically average and wet years the differences between subirrigation and no subirrigation are less pronounced or even negligible, which is logical as if there is no moisture deficit, actual plant transpiration cannot increase either. Given the resistance to downward seepage and MLG, field site A can be considered as a location with average suitability for subsurface irrigation in terms of geohydrological characteristics in the sandy Pleistocene uplands of the Netherlands compared to field sites B, C and D. Due to the differences in geohydrological conditions, the distribution of water supply over the water balance components differs strongly for all four sites and herewith the hydrological propagation of subirrigation. A higher hydraulic resistance below the subsurface drains could reduce the downward seepage due to CDSI (up to 45% with high resistance to 81% with low resistance in the field sites studied). Furthermore, ditch drainage losses can be avoided by adapting the surface water level to the raised groundwater level. The field setup and modelling procedure that we developed can support in the design of CDSI systems for a range of geohydrological settings, including quantification of required water supply rates for different management strategies of CDSI systems, crop characteristics (like rooting depth) and meteorological conditions.

To what extent could external water supply for subirrigation be reduced by automatic control of CDSI systems in relation to crop water demand?

Dynamic control of CDSI can decrease the water supply significantly compared to fixed CDSI systems, because the dynamic control of CDSI takes into account the plant water demand, the actual soil moisture conditions and the weather forecast in determining the required pit water level. However, the water demand for subirrigation is strongly related to the meteorological conditions. Model simulations show that the water requirement can be reduced by 60 mm (dry growing season), 253 mm (average growing season) and 348 mm (wet growing season) using a dynamically managed pit water level compared to using a fixed water level. Moreover, water supply can be reduced even further when taking into account environmental characteristics, crop characteristics and crop management (up to 100 mm). Higher ditch levels and higher hydraulic resistance to downward seepage in the subsoil reduce drainage and seepage losses, respectively, resulting in a lower water supply. Water supply reduces even further for crops with a deeper rooting system as deeper groundwater levels are sufficient. Finally, accepting 10% daily crop drought and oxygen stress reduces the water supply requirement with 235 to 628 mm (dry vs wet growing season) using a dynamically managed pit water level compared to using a fixed pit water level. So, external water supply for subirrigation can be reduced by automatic control of the pit water level (by changing crest level and water supply rate), while maintaining crop yield or accepting e.g. 10% reductions.

To what extent can regional upscaling of CDSI be supported with available surface water and how can an SDM support water management authorities in decision-making?

CDSI could contribute to regional water management strategies, but responsible implementation is needed. Upscaling of CDSI shows non-linear propagation in hydrological fluxes in which three phases can be identified, relevant in the context of the regional water management: 1) sufficient surface water is available for upscaling CDSI, with little impact on the regional surface water availability, 2) sufficient water is available for upscaling, but the surface water level drops sharply due to subirrigation, which increases the water demand for subirrigation and negatively impacts regional water availability and 3) insufficient surface water is available for upscaling as the surface water level drops too far, negatively impacting regional water availability and water availability for CDSI and herewith crop growth. The local measure CDSI could contribute to regional water management, but the results of phase three shows that subirrigation could simultaneously increase pressure on regional surface water availability, whereas its effect on higher crop water availability remains negligible. Since surface water is not infinitely available, surface water should be balanced across human and ecosystem needs. Therefore, stakeholders in the water system must agree on the extent to which CDSI can be implemented by farmers and facilitated by the water management authority. The developed SDM might support stakeholders to investigate whether CDSI can be scaled up within a region in relation to the surface water availability and the key factors influencing it. Limitations on regional water availability could depend on geohydrological characteristics and regional water management. A higher drainage resistance to the ditch (a geohydrologic characteristic) or a lower GWL_{pref} (a local

water management setting), ensures that less water is needed to meet GWL_{pref} and, as a result, more water remains regionally available. In addition, the regional water management determines the inflow to the regional surface water, weir management and minimal required surface water level. In general, measures to increase regional surface water availability may provide more opportunities for upscaling CDSI and thus subirrigation.

6.2 The measure CDSI as contribution to a climate robust water system

6.2.1 Considerations before implementing CDSI

Living in a delta like the Netherlands means continuous fighting against water (Blankesteijn and Pot, 2024). The Dutch water management strategy shifted from drainage to drainage + retention to drainage + retention + recharge in the 20th century as discussed in chapter 2. However, a combination of the current Dutch landscape, which is still designed to discharge water, an expected increase in mismatch between water demand and water supply and an increase in weather extremes requires measures for a robust water system in the future (National Deltaprogram, 2021). Measures could have a more natural approach (restoring the water system or adapting land use) or a more technical approach (dikes, weirs). In this thesis, I focused on the (technical) hydrological measure CDSI.

Hydrological measures on agricultural fields can mitigate the impacts of dry and wet periods. Short-term measures as sprinkler irrigation or water retention using small weirs, can be taken relatively easily (Van den Eertwegh et al., 2021), but often show limited effectiveness for long-term challenges or may negatively impact other water users. Conversely, long-term measures as higher surface water levels and spatial planning changes (Nationaal Deltaprogramma Zoetwater, 2025) are often difficult to implement due to their impact on land use functions. In addition, adaptation measures for wet circumstances can make areas more vulnerable to drought and vice versa (Bartholomeus et al., 2023). Therefore, the implementation of a measure requires an understanding of its local effects as well as how a measure can be integrated into the regional water management.

The measure CDSI, explored in this thesis, shows promise to contribute to a climate-robust soil-water system from a field scale perspective. However, its integration into regional water management requires careful evaluation. Section 6.1 outlined the hydrological opportunities and limitations of CDSI. The following paragraphs elaborate key considerations for implementation.

The intended *purpose* of CDSI is a key consideration. Historically, drainage pipes were installed to improve crop conditions by removing excess water. These systems are already installed in 34% of Dutch agricultural land (Massop and Schuiling, 2016). So, in the short term, converting traditional drainage systems to CD is a relatively small modification, while it immediately contributes to improved water management. The effectiveness of converting CD to CDSI depends on the regional water management strategy: water availability for subirrigation, the geohydrological characteristics and surface water management. In the long term, soil and water should guide decisions about which crops are

grown where. CDSI can serve as a technical measure to further optimize water management.

Requirement	Details	Conclusion
1. Pit management	Continuous or dynamic pit water level	A control pit with a fixed crest level and continu water supply requires more water than pumping using a dynamic crest level and water supply rate.
2. Surface water management	Ditch level	A ditch level adapted to the raised groundwater level due to subirrigation avoids unneccasary drainage to the ditch.
3. Meteorological characteristics	Dry or wet period in growing season	CDSI systems increase crop transpiration mainly in drier years and less or even negligible in average and wetter years.
4. Geohydrological characteristics	Presence of hydraulic resistance	A hydraulic resistance in the soil limits excessive downward seepage.
5. Crop characteristics	Root type (shallow or deep)	Shallow rooting systems require more water supply than deeper rooting systems.
6. Source of water (local scale)	Local water quality	Sufficient water quality could avoid negative effects on the quality of the groundwater due to downward seepage.
7. Source of water (regional scale)	Regional water availabilty	Upscaling of CDSI shows non-linear propagation in hydrological fluxes in which three management phases might be distinguished. Surface water availibility is: 1. sufficent for upscaling CDSI, with little impact on the regional surface water availability 2. sufficient for upscaling CDSI, but surface water level drops sharply, impacting regional water availability 3. limits the amount of subirrigation, restricting crop water availibility & putting a large pressure on regional surface water levels
8. Management and maintenance	Design, construction and management	The design, construction and management of a CDSI system must include the water composition of subirrigation source to avoid clogging.
9. Stakeholders	Policy makers and farmers	Understand the propogation of a local measure through the regional water system.

Figure 6.2: Overview of nine requirements that might be considered before implementing CDSI.

CDSI systems can fulfill a dual purpose: improving crop growth conditions while also contributing to the recharge of the regional water system. The main purpose of CDSI implementation could be to improve crop growth conditions. CDSI systems can i) discharge water to avoid waterlogging, and ii) retain or iii) recharge water to prevent agricultural drought. This study shows that crops benefit mainly from water recharge in dry growing seasons and little to none in average and wet growing seasons, as sufficient water is available anyway. Additionally, the results show that only a minor part of the supplied water contributes to increased plant transpiration. Most of the supplied water leaves the system as ditch drainage and as downward seepage to the deeper groundwater. In order to actually improve crop growth conditions, sufficiently high surface water levels and hydraulic resistance to downward seepage are required to retain as much water as possible in the soil. So, if the only objective of CDSI implementation is to improve crop growth conditions, the question arises whether the investment in CDSI is warranted, given the geohydrological boundary conditions, the potentially high water use for subirrigation, and the intended increase in crop yield.

A secondary purpose of CDSI implementation, identified during this study, could be to recharge the regional groundwater system. The Dutch water system is still designed to drain surface water into rivers. So, retaining more water in an area is also a step towards a more climate-robust soil-water system. To recharge the regional groundwater system, a lower or minimal hydraulic resistance below the subsurface drains is preferred. However, as discussed previously, this would impact the improved water availability for crop growth.

This therefore requires a trade-off between the two purposes: crop growth and groundwater recharge. Infiltrating external water for regional groundwater recharge also raises questions related to water quality and if the implementation of CDSI may lead to undesirable effects on groundwater quality. Investigating the effect of infiltration of external water on groundwater quality should be part of CDSI implementation.

As conclusion, with the changing climate, the conversion from conventional drainage to CD and CDSI systems is a relatively small investment on the short term, while it allows to better anticipate dry and wet conditions by retention of precipitation or infiltration of excess external water of sufficient quality, and drain water in wetter conditions.

The installation of CDSI systems should aim the dual purpose of improving crop growth conditions and recharging the regional water system while considering the nine requirements mentioned in Figure 6.2:

1. A CDSI system containing a dynamic crest level and a dynamic pump management for an appropriate water level in the control pit on a daily basis based on actual soil moisture conditions and weather forecasts ensures a smarter use of water, which is a management consideration for the farmer.
2. A ditch level adapted to the raised groundwater level due to subirrigation avoids unnecessary drainage to the ditch, which is a water availability consideration for the water management authority.
3. A minor part of the supplied water contributes to increased plant transpiration and thereby, crop benefits are mainly in dry growing seasons and little to none in average and wet growing seasons, as sufficient water is available anyway, which is important for the intended goal of CDSI implementation and a consideration for the farmer.
4. A hydraulic resistance below the subsurface drains limits excessive downward seepage which is needed for sufficiently high groundwater levels, but limits regional groundwater recharge. Therefore, a certain optimum should occur to fit the dual purpose of CDSI.
5. Crops with deeper roots require less water for subirrigation than crops with shallower roots, which makes this a consideration to water availability.
6. Sufficient water quality avoids negative effects on the groundwater quality, further discussed in section 6.2.2.
7. CDSI is only a meaningful measure if sufficient surface water is available for subirrigation.
8. The design, construction and management of a CDSI system must consider the water composition of the subirrigation source to avoid clogging, discussed in section 6.2.2.
9. Collaboration between the water management authority and the farmer(s) is required to make agreements on when and how much surface water can be used for CDSI.

The considerations mentioned above are the key results of this thesis, which provides guidance for the practical implementation of CDSI. However, further research is needed to investigate the exact locations for suitable agricultural fields to implement CDSI. Besides the practical implementation, further research is needed to explore how CDSI can contribute to the water transition and the transition to a climate-resilient and water-robust Netherlands in 2050, for example within larger research projects such as the Dutch freshwater program (in Dutch: Deltaprogramma Zoetwater).

All-in-all, land use changes are often triggered by social and economic changes (Chapter 2), complemented by technical measures. Subsurface drainage and land consolidation were desirable solutions to reduce food prices after World War II, but nowadays lead to greater vulnerability to drought. It is therefore important that implementation of CDSI, as a solution to the imbalance between water demand and supply, does not lead to future complications. This may happen if not all nine considerations are taken into account prior its implementation. Based on both historical knowledge and insights gained from this study, I conclude the following. We are currently in the middle of changes: a changing climate (more dry and wet extremes), increasing water demand by industries, agriculture and nature, and decreasing regional water availability. There is a need to rethink the current landscape design, considering the physical limitations to the soil-water system. This might mean that geohydrological conditions are more leading in choices about land and water use (Nationaal Deltaprogramma Zoetwater, 2025), which implies accepting that not all types of land use are feasible in every location at all times. For example, to grow more drought-resistant crops in drier areas and to grow more flood-tolerant crops in wetter areas. The measure CDSI could then be a technical measure to be used on agricultural fields where soil and water was leading in the decision to grow crops suitable for that location, but there are still wet and dry conditions in the field.

6.2.2 Insights from associated research

The composition of the supplied water (requirement 8, Figure 6.2) was important in the field experiments. The field experiments were designed to understand the hydrological effects of CDSI systems, but field experiments could also lead to water quality issues. These issues were only briefly described in chapter 3, because they were outside the scope of that chapter, but in this section, I will elaborate a bit further on the water quality effects in the field experiments of this thesis.

The water quality of the supplied water could affect i) the management of the CDSI system and ii) the quality of the regional (surface and ground) water. Firstly, depending on the composition of the supplied water, clogging may occur as described in chapter 3 and De Wit et al. (2023a). Clogging could be caused due to i) ditch debris in the pump filter located in the surface water, ii) iron precipitation from infiltration with oxygen-free, iron-rich groundwater or iii) high biological activity and nutrients in water (e.g. in effluent). Clogged drains can be flushed, but often CDSI systems are not designed for flushing. In the field pilot in America, a modification has been made to be able to flush the CDSI system (Figure 6.3). After flushing, the *GWL* raised directly (Figure 6.3) which improved the crop water availability again. Secondly, infiltrating supplied water could mix area-specific with area-

foreign water which could result in water with undesirable water quality. As we intend to take care of a healthy environment, the water quality of infiltrated water should be known. Especially with supplying effluent (Narain-Ford et al., 2021) because, once water is infiltrated deeper into the soil, this could affect different economic sectors in the coming decades as they depend on both sufficient water availability and suitable water quality. Additionally, lateral drainage increases through applying subirrigation, which could affect the surface water quality. Given that surface water is used for multiple uses, such as for nature or for drinking water, potential water quality effects must be carefully considered. Lastly, supplied water to the soil might result in absorption of substances to the soil (De Wit et al., 2023a). As conclusion, it is necessary to understand the composition of the water supply source to avoid negative effects on the drainage system and on the environment.

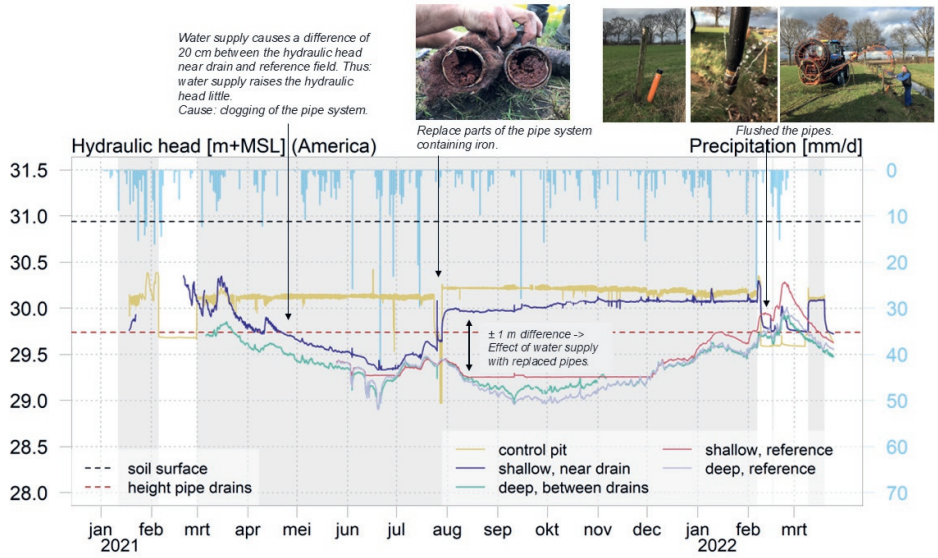


Figure 6.3: Hydraulic heads during a clogged CDSI system (January – July 2021) and after flushing the CDSI system (August 2021 – March 2022) of the field experiment in America. The grey areas represent the water supply periods. Figure obtained from De Wit et al. (2024a).

The *management* of a CDSI system (requirement 6 in Figure 6.2) involves both the farmer and the water management authority. Subirrigation raises the *GWL*, which increases the difference between the *GWL* and ditch level and thereby ditch drainage. To reduce ditch drainage losses, the water management authority could adjust the surface water level to the *GWL*. The farmer can make smart use of surface water by setting the crest height to an appropriate water level to drain, retain or supply water, to anticipate dry and wet conditions. Since the water management authority is responsible for managing the surface water, and the farmer uses this surface water for subirrigation, both share responsibility for the CDSI system, as described below.

During periods of surplus (mid-December 2024 to end-January 2025, Figure 6.4), water is retained in the soil while ensuring sufficient capacity for precipitation. This is crucial to

prevent too wet soil profiles, which can lead to flooding or oxygen stress in crops. If the *GWL* remains relatively shallow, making the field too wet for land work, two challenges may arise:

1. Simultaneous drainage by multiple farmers (early February 2024 and 2025, Figure 6.4) may overload the regional surface water system, requiring the water authority to respond adequately managing the surface water level.
2. Precipitation surplus is needed to restore the *GWL* after the land work, but this may not occur.

In the example shown in Figure 6.4, a precipitation deficit period occurred in March – April 2024, making it impossible to retain water. In this particular situation, the farmer was able to supply water with a pump. However, farmers without excess to a pump may use sprinkler irrigation to support crop germination during dry periods. This example illustrates that even after a wet period with sufficient surface water for retention, draining water followed by a lack of precipitation can lead to drought stress and the need for irrigation. As weather extremes become more frequent and intense (Spinoni et al., 2019; Teuling, 2018), further research into smarter water use, combined with season weather forecasting (e.g. extension of the algorithm of chapter 4) could contribute to a more climate robust soil water system.

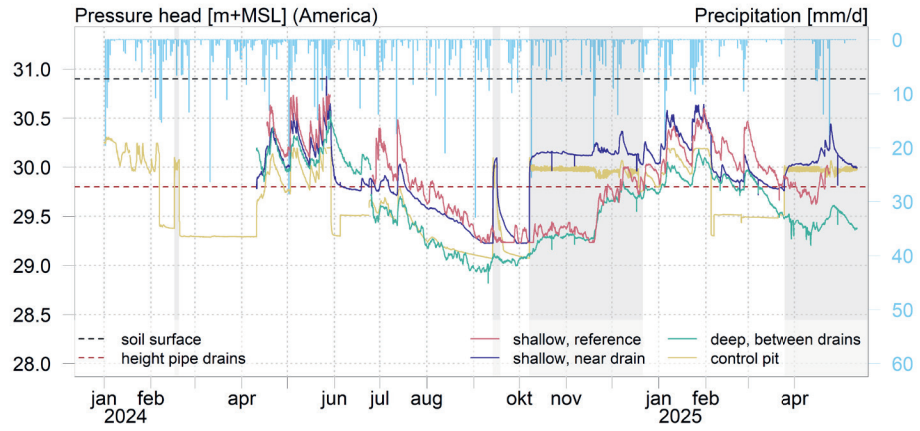


Figure 6.4: Hydraulic heads January 2024 – April 2025 for the field experiment in America. The grey blocks represent the subirrigation period.

6.2.3 Open research challenges

This research has improved the knowledge base on CDSI, supporting decision-making by farmers and water managers on whether to implement the measure within their water management strategy (section 6.2). This enhanced understanding supports the transition from traditional drainage systems focused solely on discharge to controlled drainage with subirrigation systems focused on retention + discharge + recharge. However, further research is needed to identify suitable agricultural fields for implementing CDSI, for

example to support the development of more climate-resilient and water-robust Pleistocene uplands of the Netherlands. The research challenges in the following paragraphs may contribute to this goal.

The *financial investment* for implementing CDSI is relatively low when converting traditional drainage systems to CDSI, but higher when installing new CDSI pipes. However, hardly any study investigated the financial viability of CDSI. Edwards and Thurman (2022) state that, logically, the economic value of (traditional) drained agricultural fields increased in the United States. Future Water et al. (2010) focused on automatic CD (no CDSI) as measure to reduce peak flows and described that the costs of implementation of CDSI were lower than the additional regional water management costs for peak flows e.g. additional storage of pumping capacity in times of flooding. Further research could focus on evaluating a cost-benefit analysis of implementing CDSI considering both the advantages for a farmer (crop yield) and the benefits for the regional water system (reducing peak flows and recharging the groundwater system). Additionally, these findings could be compared to the costs and benefits of alternative measures to anticipate dry and wet conditions, both for the farmer and for the regional water system.

A *suitability map for CDSI* could indicate locations suitable for CDSI implementation. Van Bakel et al. (2013) created a suitability map of the Netherlands for climate adaptive drainage (CAD, Van den Eertwegh et al. (2013)). More recently, a CD suitability map was published for Flanders, Belgium[2]. The CDSI suitable map for the Netherlands might start with geological requirements for CDSI implementation on sand, peat and clays in the Netherlands. This study focused on the Pleistocene uplands of the Netherlands (South and East of the Netherlands), Hunink et al. (2021) focused on CDSI systems to avoid land subsidence due to peat oxidation (peat soils, western part of the Netherlands) and Terink et al. (2023) focused on CDSI system to mitigate salinization due to supply/recharge of freshwater (clay soils, western part of the Netherlands). The next step for a suitability map could be to evaluate future regional surface water availability under changing climate conditions. This could help to indicate water supply areas for CDSI (including surface water sources or external sources as treated effluent). The combination of suitable soil types, geohydrological characteristics and water supply areas could form the base towards a map that identifies locations suitable for CDSI implementation. Subsequently, it would be valuable to expand this map to assess the scalability of CDSI in relation to surface water availability (Chapter 5).

The measure CDSI might contribute to a more climate robust soil-water system. Simultaneously, CDSI may not be the most suitable measure in every location at all times. Further research is needed to compare CDSI with other irrigation measures, as drip or sprinkler irrigation. Drip irrigation is often used to supply water precise and a low rate (Bhavsar et al., 2023). Sprinkler irrigation is often used to irrigate at specific times of the year, such as during seed germination. Every irrigation gift is approximately 25 mm at the Dutch sandy soils (Spruijt and Russchen, 2015). Assuming 500 mm/y water supply for

[2] https://www.peilgestuurdedrainage.be/geschiktheidskaart-online-v1

subirrigation, this volume corresponds with 20 times sprinkler irrigation. Disadvantages of sprinkler irrigation compared to CDSI are i) more water losses due to water drift and evapotranspiration of irrigation water (Yazar, 1984; Zazueta, 2018), ii) sprinkler irrigation requires more labor of the farmer since (s)he has to monitor and move the sprinkler system now and then (Salvador et al., 2011) whereas a pipe system is fixed in the ground, and iii) sprinkler irrigation is only used during dry periods, when water availability is limited (Wriedt et al., 2009) and water demand from multiple uses is high. In contrast, CDSI can be applied earlier to store water and create a buffer in the soil. Further research is needed to compare CDSI with other (irrigation) measures, including practical implementation aspects, financial investments, water use efficiency, and associated management tasks/ labor, to increase decision-making on irrigation measures.

In conclusion, it is important to consider that sprinkler irrigation is typically aimed at improving crop conditions at a specific moment in time. In contrast, CDSI systems should aim to serve a dual purpose: enhancing crop growth conditions while simultaneously contributing to the recharge of the regional water system, taking into account the nine requirements shown in Figure 6.2.

6.3 Science to practice and society

6.3.1 From science to practice | Field experiments vs modelling

Scientific research varies between fundamental research to applied research (Baimyrzaeva, 2018). Fundamental research is essentially basic research: research to expand scientific knowledge without necessarily a direct aim. Conversely, applied research is acquiring knowledge towards a specific aim. A specific aim often originates from a combination of a specific situation that conflicts with a perspective, creating a demand for an adapted or new solution. This is also called a bottom-up approach (Thomann et al., 2018).

Drainage systems have been used in the Netherlands for decades (= current situation). However, due to the combination of a water management focused on drainage, low groundwater levels and a changing climate, agricultural fields and natural areas in the Dutch Pleistocene uplands experience drought during prolonged dry periods, but also floods in periods of heavy rainfall (= current perspective). Droughts are worldwide the main drivers of crop loss (Cottrell et al., 2019) with a major impact on the world economy and food security (Tramblay et al., 2020). The economic cost to the Dutch agricultural sector could be 1.5 billion euros in an extremely dry year (Van Duinen et al., 2015). In addition, farmers are directly (financial) affected by yield losses, which also, among other things, triggers them to look for measures as CDSI (= adapted solution). However, the measure CDSI requires (surface) water, which is management by the water management authorities in the Netherlands. Therefore, the water management authorities should also be involved in CDSI research to understand the hydrological effects of CDSI on the water system. The collaboration between farmers, water management authorities and researchers makes the research of this thesis a bottom-up approach.

A bottom-up approach often lies at the interface of fundamental and applied research (Baimyrzaeva, 2018). Therefore, in this study, a combination of field experiments and modelling is applied. Field measurements contain uncertainty (McMillan et al., 2018), but field measurements are also needed to embed a measure in the real-world with numerous interactions (Baimyrzaeva, 2018). Moreover, measurements over a longer period show trends and natural cycles (Stewart, 2015; Tetzlaff et al., 2017) which might take years in environmental studies (Körschens, 2006). The field pilots used in this thesis provided an opportunity to take measurements to understand the real-world situation/ effects of CDSI better. This included changes in groundwater level due to CDSI, water use, effects on crops, management of both the farmer and the water management authority and different types of clogging (Figure 6.3, De Wit et al. (2023a)). Field pilots are thus important for stakeholder interactions, and the related measurements are necessary as basis to i) truly understand the system, ii) set up the parameterization of models, and iii) calibrate and validate models. Therefore, field pilots are essential to bridge scientific research to the real-world experience.

Hydrological models vary in complexity and temporal and spatial resolution, all with their own strengths and limitations (Fatichi et al., 2016). Although all models contain uncertainty (Herrera et al., 2022), socio-environmental modelling expresses physics-like confidence (Puy et al., 2025). A model choice might be based on research objectives and data availability (Brauer et al., 2014; Wagener et al., 2001). In this study, I used the process-based model SWAP (Heinen et al., 2024; Kroes et al., 2017) calibrated with PEST (Doherty, 2010), which was able to reproduce field measurements as described in chapter 3. This study shows that the model is able to simulate the required water supply and the water level in the control pit of the CDSI system dynamically. Furthermore, the model results led to insight into the water balance components that cannot be (easily) measured in the field. In addition, the model provides insight into effects of meteorological conditions that were not part of the experimental periods.

The last part of this study focuses on how CDSI fits into regional water management and moreover, how it supports decision-making. Translating hydrological results into products supporting decisions is a challenge (Vogel et al., 2015). Therefore, system dynamics models are increasingly used in hydrology to support policy decisions and design (Mashaly and Fernald, 2020; Phan et al., 2021). Since SDM is relatively easy to understand, it might provide insights in scaling of local measures, which is nowadays a key issue in the Netherlands (National Deltaprogram Fresh Water, 2025). However, to be able to create a good SDM, stakeholder involvement with local experiences is essential (Stanghellini, 2010). In this study, I worked together with researchers, farmers and the water management authority to include their local knowledge. The involvement of stakeholders within this study is further described in section 6.3.2.

6.3.2 From science to society | Stakeholder engagement

Stakeholder involvement in science is growing (Koontz, 2005; Lawrence and Deagen, 2001), especially in relation to environmental challenges (Johnson et al., 2004; Rowe and Frewer, 2000) like this study. Environmental challenges are seen as complex where stakeholder

interests may conflict (Grimble and Wellard, 1997). Stakeholder involvement requires choices on *who* to involve and *how* to involve them (Mitchell et al., 1997). Many theories are available to classify stakeholders. Grimble et al. (1995) classified a stakeholder matrix according to importance and influence. Aggens (1983) defined stakeholders by the human energy needed to sustain them varying from decisions makers to people who were not initially involved in a topic. The European Commission (2003) developed a method within the Water Framework Directive to classify stakeholders and to identify the degree of involvement of each actor at each stage (Figure 6.5-I).

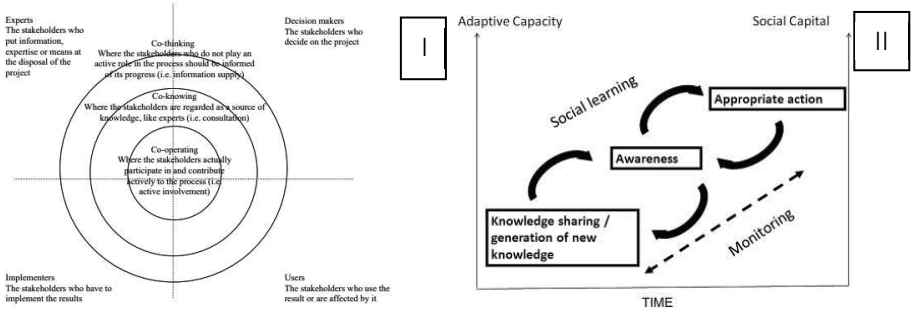


Figure 6.5: Overview to classify stakeholders and identify the degree of involvement. Left figure (I) is adapted from European Commission (2003), the right figure (II) is adapted from Cundill and Fabricius (2009).

This thesis was part of the programs Lumbricus and KLIMAP (Chapter 1), which consisted of a consortium of water management authorities, farmers, municipalities, industries, provinces and research institutes. Although stakeholder involvement was not the focus of this study, stakeholder involvement was important throughout the research to exchange knowledge and to provide (critical) reflections on the research.

Stakeholders worldwide are already involved in studies showing an increase in collaboration, transparency, sharing of information and the ability to feed policy discussions (Becker et al., 2005; Gray and Kalpers, 2005; Poulsen and Luanglath, 2005). All these elements contribute to an increase in adaptive capacity of stakeholders and social capital between stakeholders (Figure 6.5-II). Adaptive capacity is defined as the ability to adapt to change and respond to disturbances (Adger, 2010; Armitage, 2005). Social capital refers to features of daily life such as trust, network and norms that contribute to working together toward one common goal (Putnam, 2015). Moreover, social capital could result in higher adaptive capacity (Cundill and Fabricius, 2009). So, the collaboration of stakeholders including a sufficient balance between adaptive capacity and social capital is crucial to implement measures (Connick and Innes, 2003). For the research presented in thesis, collaboration with stakeholders could result in more awareness for the freshwater challenges in the Netherlands, and simultaneously, collaboration with stakeholders within the process of CD conversion to CDSI could create i) better understanding of how CDSI functions, ii) understanding the suitability of locations for CDSI implementation, and iii) support, if the location suits, to convert existing drainage to CDSI.

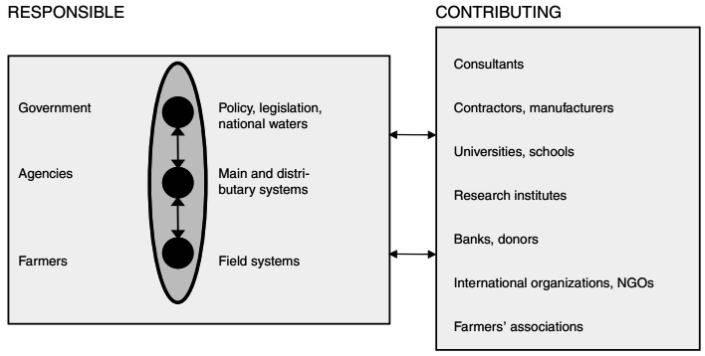


Figure 6.6: Schematization of actors in drainage water management within agricultural water management. Figure is adapted from Schultz (2001).

Reed (2008) states that stakeholder involvement is most successful by including them as early as possible in the process and also continuously during the process. In addition, involving stakeholders might also avoid a lack of knowledge about a new measure (Campana et al., 2022). Water management authorities and farmers are primarily responsible for drainage, while other parties contribute to it (Figure 6.6, Schultz (2001)). Because this thesis was part of the Lumbricus and KLIMAP program, it provided the opportunity to collaborate with stakeholders. In this study, the water management authority is responsible for the drainage and surface water policy. The agency is the drainage company, who can actually install or adapt the drainage systems. They could indicate whether things can be actually applied in the field. The farmers are the users of the CDSI system. Farmers were involved in the research to take manually *GWL* measurements (Breman et al., 2019) resulting in i) a learning-based process (Cundill and Fabricius, 2009) to create more awareness of the CDSI water management system (Figure 6.5-II) and ii) verifying the automatic measurements with the manual measurements. The involvement of stakeholders within the process may improve the research (Edelenbos and Klijn, 2006) and might create more willingness to implement a measure (Thomann et al., 2018) such as CDSI.

Closely connected to stakeholder involvement is scientific communication. Although a lot of good research is being done, much research may remain 'on the desk'. The responsibility of researchers might be to communicate their science in a broader way than scientific papers. However, the difficulty of communication with stakeholders is often the use of different terminologies and methodologies (Getson et al., 2022). Scientific communication is only useful if the communication reaches the stakeholders with the information they need and in a form they can use (Fischhoff, 2013; Van Duinen et al., 2015). While the public might be informed by popular science as news paper science, blogs and television items (Bubela et al., 2009), scientists might be interested in the data and general knowledge collected in this study. Therefore, I created a framework of scientific communication methods related to stakeholders within and outside my PhD-research with the aim to inform society about controlled drainage with subirrigation and its relation to freshwater management (Figure 6.7). Setting up a framework helped me to define the stakeholders with an appropriate

communication method. Part of the communication is listed in 'List of publications'. Since this study strongly focused on field experiments conducted in the Netherlands, drainage developments and stakeholders, I have written an extensive summary in Dutch which has also been published in a Dutch professional journal. Not all the communication methods need to be agreed upon before conducting research; the framework could also help to remind yourself to continue these communications during everyday research. For example, presenting and applying the field observations through an online dashboard method was an idea of researchers and the water management authority during the project. All in all, I would encourage scientists (at the start of a project) to think about *who* you would like to inform about your research and *what* the appropriate method for communication could be. Then, applying communication throughout the project might become easier.

All-in all, conducting an applied PhD study, as part of a larger research program, and conducted at a research institute in collaboration with a university, was a valuable process. The regional freshwater program KLIMAP, supporting the national freshwater program, gave me the opportunity to closely work with stakeholders where ultimately the freshwater challenges came from (= bottom-up approach). In addition, working closely together with stakeholders also resulted in sharing knowledge and keeping research questions focused (Bruine de Bruin and Bostrom, 2013). Although applied research has many advantages, it may also require more than fundamental research in terms of validity, reliability, effectiveness, efficiency, feasibility, relevance and sufficiency (Baimyrzaeva, 2018). So, although conducting a PhD within both an applied research institute and a university can sometimes be challenging, I encourage such tracks for more PhD studies, to be better embedded in science, practice and society.

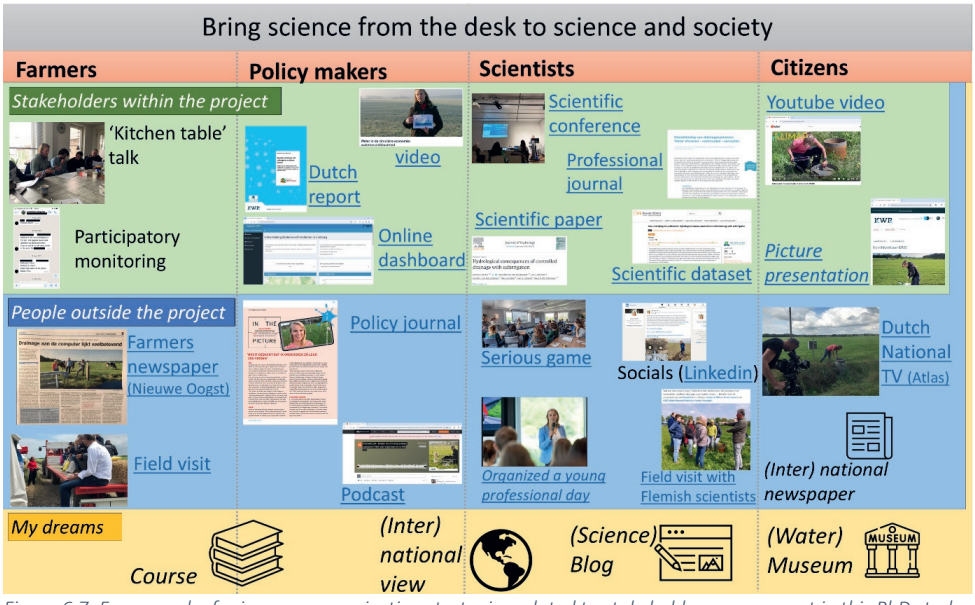


Figure 6.7: Framework of science communication strategies related to stakeholder engagement in this PhD study with the aim to bring science from the desk to science and society.

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Chapter 2 Development of subsurface drainage systems: discharge – retention - recharge.

Conceptualization of the work:	GvdE, JdW, JvD, RB
Data collection:	JdW, JvD, RB
Modelling, data analysis and interpretation:	JdW, JvD, RB
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Chapter 3 Hydrological consequences of controlled drainage with subirrigation.

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Chapter 4 Controlled drainage with subirrigation systems: reduce water supply by automatic control.

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Chapter 5 Subsurface irrigation in regional water management: Support decision making using a system dynamics approach.

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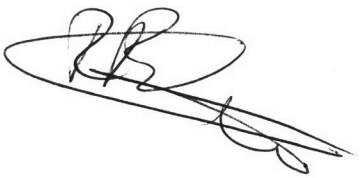
Chapter 6 Synthesis. I prepared the outline for the synthesis, discussed it with JvD and RB and then wrote the synthesis. The synthesis was reviewed by CR, JvD and RB.

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REGELBARE DRAINAGE MET SUBIRRIGATIE: HYDROLOGISCHE MOGELIJKHEDEN EN RANDVOORWAARDEN (UITGEBREIDE NEDERLANDSE SAMENVATTING)

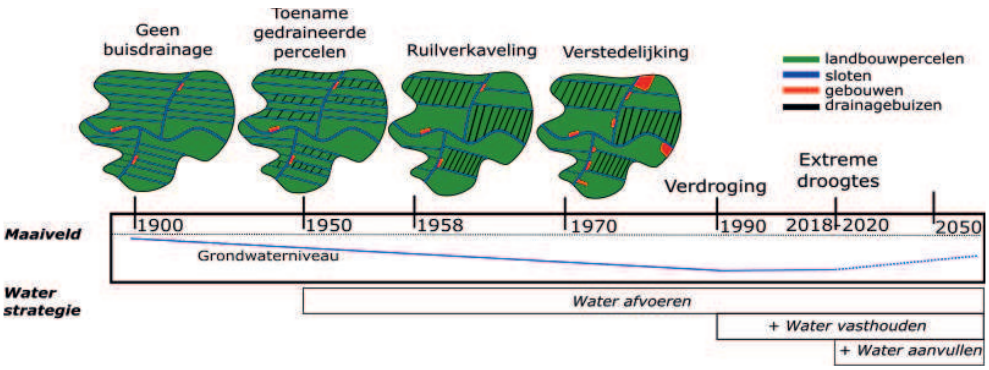
YOUR PRESENT CIRCUMSTANCES DON'T DETERMINE WHERE YOU CAN GO, THEY MERELY DETERMINE WHERE YOU CAN START. - NIDO QUBEIN

De uitgebreide samenvatting is gebaseerd op:
De Wit, J., Van den Eertwegh, G., Van Huijgevoort, M., Van Dam, J., Bartholomeus, R. (2025). Regelbare drainage met subirrigatie: Hydrologische mogelijkheden en randvoorwaarden. Stromingen 2025 (31), nr. 3.

Regelbare drainage met subirrigatie (RDS) is de laatste jaren onderzocht als maatregel om te anticiperen op de onbalans tussen watervraag en wateraanbod op de Nederlandse hoge zandgronden. In Haaksbergen startte een veldexperiment met regelbare drainage met subirrigatie. Vervolgens zijn diverse onderzoeken zoals Boer-Bier-Water, Programma Lumbricus en TKI-project KLIMAP uitgevoerd waarbinnen veldproeven zijn opgezet in Lieshout, America en Stegeren. In dit artikel beschrijven we de algehele resultaten van deze veldproeven. We focussen achtereenvolgens op de metingen in de veldproeven, de modellering (SWAP) van de verandering in grondwaterstanden, vochtgehaltes en hydrologische fluxen, de mogelijkheden om slimmer water aan te voeren op basis van een algoritme dat metingen, weersverwachting en hydrologische modellering combineert, en als laatste de opschaling van RDS van perceel- naar regionale schaal, gemodelleerd met een systeemdynamisch model. Tot slot geven we een aantal handvatten ter ondersteuning van de keuze om RDS al dan niet te implementeren.

Inleiding

Zoetwater is noodzakelijk voor natuur en waterafhankelijke sectoren als landbouw, drinkwater en industrie. De watervraag zal in de toekomst echter stijgen door, onder andere, economische groei, verstedelijking en voedselproductie, terwijl de beschikbaarheid van zoetwater afneemt. Daarnaast zullen, door klimaatverandering, weersextremen (zowel drogere als nattere perioden) frequenter en extremer voorkomen (Spinoni et al., 2019; Teuling, 2018). Maatregelen in het Nederlandse waterbeheer zijn nodig om te anticiperen op de onbalans tussen watervraag en wateraanbod. Een van de maatregelen die verkend wordt om anders om te gaan met water in de landbouw, is het omvormen van drainagesystemen tot regelbare drainage met subirrigatie.



Figuur 1: Tijdlijn met ontwikkelingen die het Nederlandse landschap en grondwaterniveau beïnvloed hebben. De 20e eeuw laat een dalende trend zien van het grondwaterniveau; de waterstrategie was gericht op het afvoeren van water. Om gewasgroei te bevorderen, verschoof dit rond 1990 naar i) het afvoeren van water om te natte omstandigheden te voorkomen en ii) het vasthouden van water waar nodig. Vanaf 2018 ligt er meer focus op de combinatie van i) water afvoeren om te natte omstandigheden te voorkomen, ii) water vasthouden en iii) water aanvullen om de effecten van droogte te verlichten. Figuur is ontleend aan De Wit et al. (2022).

Ontwikkeling Nederlands watersysteem

Het Nederlandse watersysteem is van oudsher ingericht op het afvoeren van water om te natte omstandigheden te voorkomen (Figuur 1). In de 20^{e} eeuw zijn veel percelen daarom

ontwaterd. Vooral na de Tweede Wereldoorlog zijn landbouwpercelen intensiever ontwaterd door de aanleg van buisdrainage om de grondwaterstanden verder te verlagen en hiermee de gewasproductie te verhogen. In 2012 was 34% van het Nederlandse landbouwareaal gedraineerd (Massop and Schuiling, 2016). Naast de ontwatering vond er tussen 1960-1980 ook intensieve ruilverkaveling plaats om landbouwpercelen te vergroten, waardoor voedselprijzen laag konden blijven. Buisdrainage/ontwatering, ruilverkaveling, verstedelijking en grondwateronttrekkingen zorgden samen voor een systematische daling van het grondwaterniveau, plaatselijk tot gemiddeld 50 cm over de afgelopen eeuw (Knotters and Jansen, 2005).

Ontwikkeling drainagesystemen

Waterbeheer met de focus op water afvoeren, lage grondwaterstanden en een veranderend klimaat zorgen ervoor dat landbouwpercelen op de hoge zandgronden droogte ervaren. Het is daarom noodzakelijk om de ontwatering te reduceren, meer water langer vast te houden waar het als neerslag valt, en gedurende het groeiseizoen hogere grondwaterstanden te realiseren. Een van de maatregelen hiervoor kan het doorontwikkelen van drainagesystemen zijn. Conventionele buisdrainage, gericht op water afvoeren, kan omgevormd worden tot (samengestelde) regelbare drainage, gericht op water afvoeren wanneer nodig en water vasthouden als er sprake is van een neerslagoverschot. Als wateraanvoer mogelijk is en er zoetwater beschikbaar is, kan het drainagesysteem ook ingezet worden voor subirrigatie om het grondwater aan te vullen. Regelbare drainage met subirrigatie (RDS) heeft dus drie doelen: i) water afvoeren wanneer nodig, ii) water vasthouden op het perceel om onnodige drainage te voorkomen en iii) grondwater aanvullen.

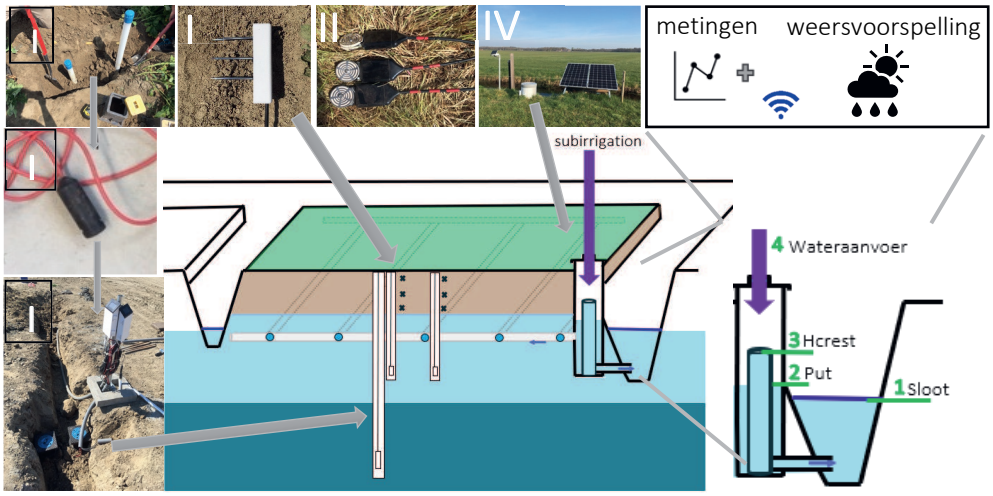
Regelbare drainage met subirrigatie

RDS bestaat over het algemeen uit een regelput waar extern water instroomt (Figuur 2). In de regelput bevindt zich een systeem (bijv. een vlotter of een balg) dat het waterniveau bepaalt tot wanneer wateraanvoer wordt toegepast. De ingestelde drempelwaarde waarboven water wordt afgevoerd wordt de ‘cresthoogte’ genoemd. De regelput is verbonden met een verzameldrain, die weer verbonden is met de drains die loodrecht op de verzameldrain liggen. Wanneer de stijghoogte in de put en de drains hoger is dan in het grondwater, vindt er infiltratie plaats. Ook in landen als Amerika, Canada, Australië, Zweden en Iran is ervaring opgedaan met RDS-systemen, zie De Wit et al. (2022).

Veldproeven RDS op de hoge zandgronden

Regelbare drainage met subirrigatie is de laatste jaren onderzocht op de Nederlandse hoge zandgronden in vier veldexperimenten: America (2017-heden, Bartholomeus et al. (2018a)), Haaksbergen (2016-2022, o.a. Stofberg et al. (2021)), Lieshout (2015-2020, Bartholomeus et al. (2018b)) en Stegeren (2018-2022, De Wit et al. (2021b)). Alle veldlocaties bevonden zich op de hoge zandgronden in Oost- en Zuid-Nederland, met verschillende bodemprofielen en geohydrologische karakteristieken, maar met op dezelfde wijze ingerichte veldproeven met meetapparatuur. Op elke locatie is de wateraanvoer, cresthoogte, het oppervlaktewater-, put-, en grondwaterniveau (tussen twee drains en direct naast een drain), de stijghoogte in een diepere peilbuis, en het bodemvochtgehalte

op 20, 40 en 60 cm-mv gemeten. Daarnaast is in America en in Stegeren de zuigspanning op 20, 40 en 60 cm-mv gemeten en op beide locaties was een referentieperceel (zonder buisdrainage) ingericht met meetapparatuur. De bron van subirrigatie was grondwater (America), gezuiverd huishoudelijk restwater (Haaksbergen), gezuiverd industrieel restwater (Lieshout) en oppervlaktewater (Stegeren).



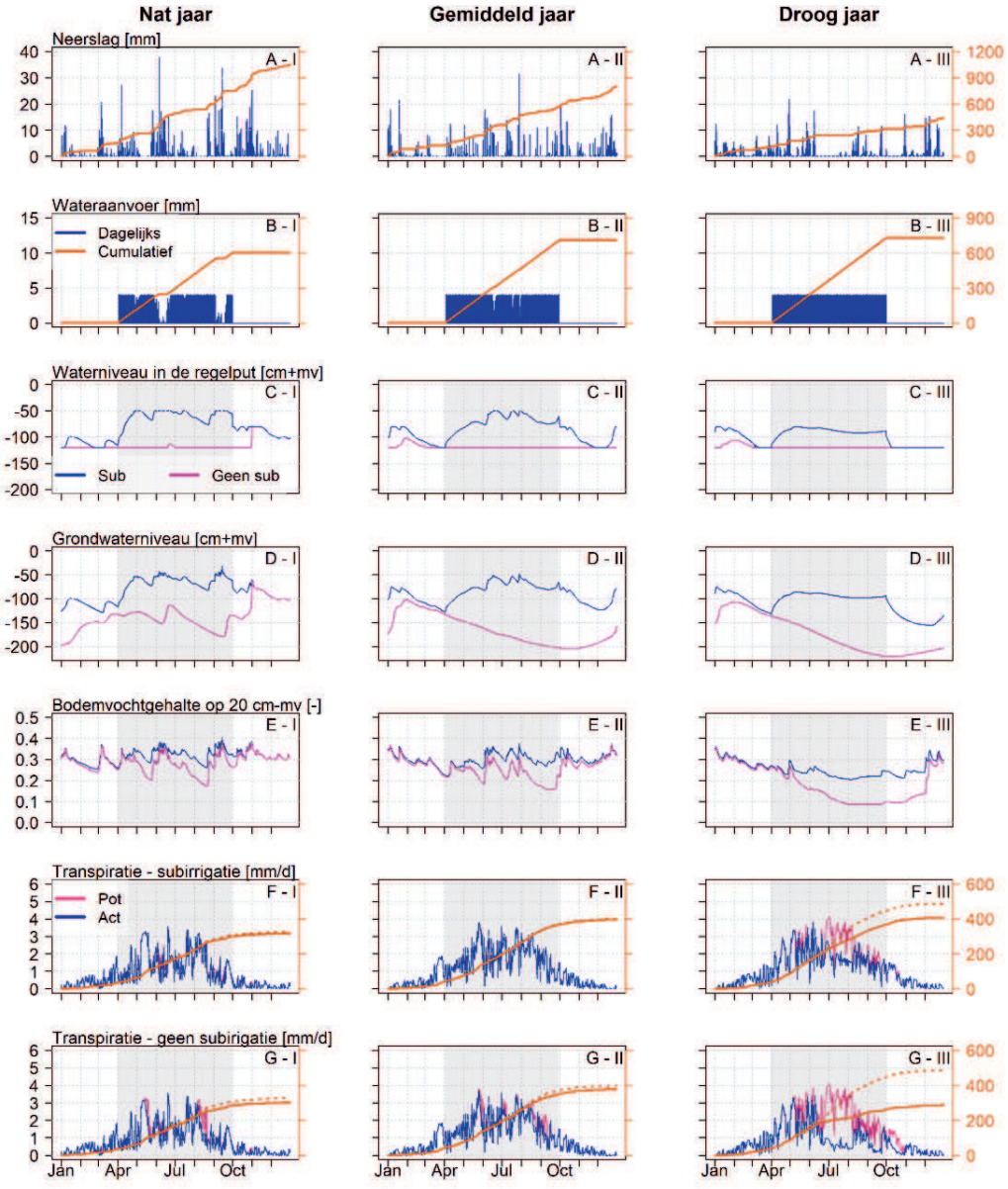
Figuur 2: Algemene opstelling regelbare drainage met subirrigatie met geïnstalleerde meetapparatuur. Meetapparatuur was: ondiepe en diepe stijghoogte (I), op 20, 40 en 60 cm-mv bodemvochtgehalte (II) en zuigspanning (III), oppervlaktewaterniveau ('Sloot'), waterniveau in de regelput ('Put'), cresthoogte ('Hcrest') en de wateraanvoer ('wateraanvoer') (IV). Figuur is ontleend aan De Wit et al. (2024c).

Lokale hydrologische effecten van RDS

Regelbare drainage met subirrigatie beïnvloedt het hele hydrologische systeem. Door RDS stijgt de grondwaterstand, waardoor ook het bodemvochtgehalte stijgt via capillaire opstijging. Een hoger bodemvochtgehalte betekent meer water voor het gewas en daardoor verhoogde transpiratie (gewasverdamping) en drogestofproductie. Een beperkt deel van het aangevoerde water komt echter maar ten goede aan het gewas. Afhankelijk van het oppervlaktewaterniveau en de geohydrologische gebiedskenmerken, stroomt een deel van het aangevoerde water naar de aanliggende sloot en stroomt een deel via wegzijging naar het diepere grondwater. Een hogere weerstand tegen wegzijging voorkomt dat het geïnfiltreerde water snel wegsijpelt naar het diepere grondwater. Een hoger oppervlaktewaterniveau, aangepast aan de hogere grondwaterstand, zorgt voor minder drainage naar de sloot.

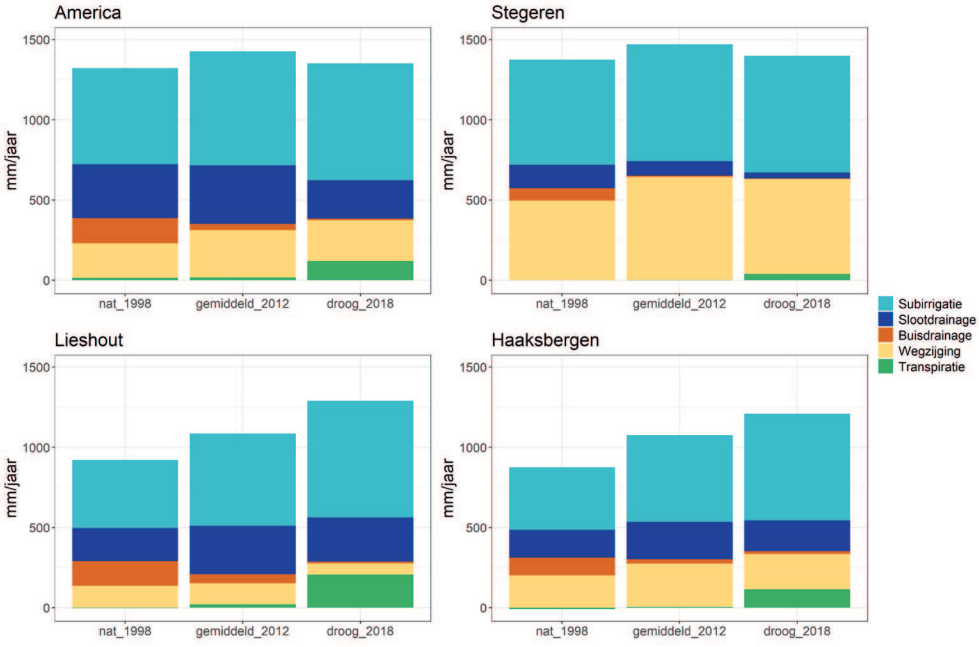
De verhoging van de grondwaterstand en de verdeling van het aangevoerde water naar hydrologische fluxen hangen sterk samen met de geohydrologische gebiedskenmerken. Door subirrigatie steeg de grondwaterstand met ongeveer 100 cm en 150 cm in respectievelijk een nat (2021) en droog (2018) jaar in America en Lieshout. Een stijging met gemiddeld slechts 30 cm door subirrigatie in Stegeren was echter onvoldoende om aan de watervraag van het gewas te voldoen. De Wit et al. (2023b) publiceerden de metingen van

de vier proeven. De metingen zijn vervolgens gebruikt om een SWAP-model te kalibreren en hiermee een langere perioden (1993-2021) door te rekenen. Uit deze modelresultaten blijkt dat de hydrologische effecten van subirrigatie ook sterk samenhangen met meteorologische omstandigheden (Figuur 3).



Figuur 3: Hydrologische effecten van RDS voor een meteorologisch nat jaar 1998 (I, linkerkant), een gemiddeld jaar 2012 (II, midden) en een droog jaar 2018 (III, rechts), gemodelleerd met SWAP (gekalibreerd aan metingen) voor de locatie America. Alle simulaties zijn uitgevoerd met subirrigatie ('sub') en zonder subirrigatie ('geen sub'). De grijze blokken representeren de periode van subirrigatie (1 april-30 september). Ontleend aan De Wit et al. (2024c).

De verdeling van wateraanvoer naar de hydrologische fluxen sloot- en buisdrainage, wegzijging en transpiratie wordt enerzijds beïnvloed door de meteorologie, anderzijds door de geohydrologie. Over het algemeen verlaat het aangevoerde water het perceel door slootdrainage of wegzijging (grondwateraanvulling), en draagt een klein deel bij aan transpiratie (Figuur 4). Hoewel de procentuele verdeling van de hydrologische fluxen varieert tussen alle veldproeven, kan de veldproef in America als een gemiddelde gezien worden ter indicatie. Voor de veldproef in America geldt dat de toename van slootdrainage (logischerwijs) hoger is in een natter jaar (56%) dan in een droger jaar (33%). De transpiratie neemt door subirrigatie in een droger jaar toe met 16% en in een nat jaar met 2% (er is dan ook minder tekort om op te heffen). De effecten van geohydrologische kenmerken zijn duidelijk zichtbaar tussen de veldproeven in Stegeren en Lieshout: bij de veldproef in Stegeren is de toename van de wegzijging gemiddeld 81%, terwijl deze bij de veldproef in Lieshout 21% is. Meer wegzijging wordt veroorzaakt door afwezigheid van een weerstandslaag en een groter stijghoogteverschil. De Wit et al. (2024c) beschrijven de details.



Figuur 4: De van subirrigatie op waterbalanscomponenten in een nat (1998), gemiddeld (2012) en droog jaar (2018). Toename in slootdrainage, buisdrainage, wegzijging en transpiratie is berekend met SWAP-modellen gekalibreerd aan veldmetingen. De grafieken tonen het verschil tussen situaties met en zonder subirrigatie (berekend als 'met' minus 'zonder'). Ontleend aan De Wit et al. (2024c).

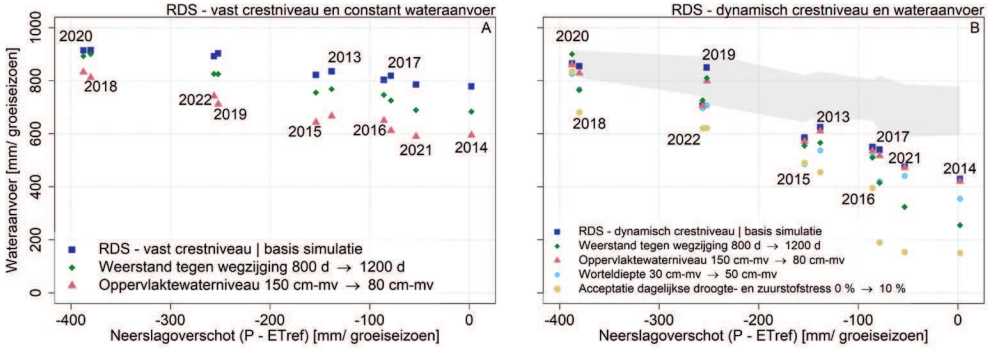
RDS 'slimmer' aansturen

De de veldproeven was de benodigde wateraanvoer zeer hoog, omdat er gedurende het groeiseizoen continu werd gestreefd naar een hoog grondwaterniveau. Er was een vast waterniveau in de put en een hoog crestniveau, waardoor de wateraanvoer varieerde tussen 500 mm en 1000 mm per jaar. De wateraanvoer kan verlaagd worden door de

benodigde wateraanvoer en het benodigde waterniveau in de put dynamisch te bepalen, op basis van een rekenalgoritme waarin de waterbehoefte van het gewas, actuele vochtconditie in het veld en de weersverwachting worden gecombineerd. Het optimale crestniveau, putniveau en de wateraanvoer worden elke dag opnieuw berekend met een gekalibreerd SWAP-model, actuele vochtmetingen uit het veld en de weersverwachting. Het algoritme berekent de vochtcondities voor de volgende dagen, waarbij er vier opties zijn voor aanpassingen in de instellingen van het RDS-systeem: 1) bij zuurstofstress: verlaag het crestniveau om water af te voeren, 2) bij onnodige drainage: verhoog het crestniveau om water vast te houden, 3) bij droogtestress: verhoog het crestniveau tot maximale hoogte en voer water aan tot het benodigde putniveau, 4) bij geen zuurstof- of droogtestress en geen onnodige drainage: geen actie, behoud het crestniveau en voer geen water aan. De verwachte zuurstof- en droogtestress en de drainageflux worden gewogen met een sigmoïdfunctie, dit betekent dat de resultaten op korte termijn zwaarder meewegen dan de resultaten op langere termijn. In de praktijk kan een dergelijk algoritme het drainagesysteem automatisch aansturen via een klimaatadaptief drainagesysteem ('KAD', Van den Eertwegh et al. (2013)), zoals technisch gerealiseerd bij de pilots in Stegeren en Haaksbergen. Recent is er een opvolgende proef met een KAD-systeem in België.

Actief sturen op de weersverwachting bespaart, logischerwijs, meer water in nattere groeiseizoenen met een relatief geringe watervraag dan in drogere groeiseizoenen met een grotere watervraag. Door actief te sturen op de weersverwachting wordt in een droger seizoen (2018; hoge verdampingsvraag, lage bodemvochtgehaltes, grote watervraag voor subirrigatie) 60 mm minder water aangevoerd, in een gemiddeld groeiseizoen (2016; gemiddelde watervraag voor subirrigatie) 253 mm minder en in een natter seizoen (2014; kleine watervraag voor subirrigatie) 348 mm minder (Figuur 5). Daarnaast kan er nog zo'n 100 mm water bespaard worden als de weerstand tegen wegzijging groter is (locatiegeschiktheid), een hoger slootpeil wordt gehandhaafd (peilbeheer van het perceel en in de regio) of een gewas met diepere wortels (gewaskeuze) wordt verbouwd. Verder kan er 235 tot 625 mm water (droog vs. nat seizoen) bespaard worden als de agrariër in de sturing op dagelijkse basis ten minste 10% droogte- (wortelzone te droog) en zuurstofstress (wortelzone te nat) accepteert. De Wit et al. (2024b) geven gedetailleerde resultaten.

Verder is het belangrijk te weten dat er een situatie kan ontstaan waarbij extra aanvoer van water niet meer leidt tot meer transpiratie. Door wateraanvoer en hogere grondwaterstanden en bodemvochtgehaltes kan de transpiratie stijgen (minder verdampingsreductie), maar op een gegeven moment wordt aangevoerd water afgevoerd naar de sloot, of het vult het regionale grondwatersysteem aan, zonder ook nog tot hogere transpiratie te leiden. In deze situatie voer je dus water aan om het vervolgens te draineren of er het diepere grondwater mee aan te vullen. Het aangevoerde water draagt dan niet meer bij aan bevordering van gewasgroei door subirrigatie, maar wel aan grondwatervulling.



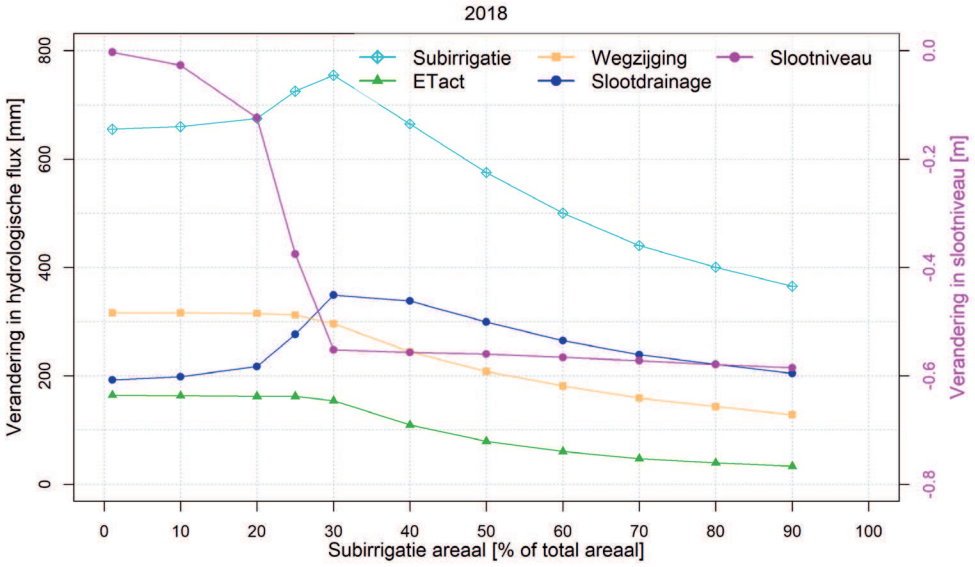
Figuur 5: Het berekende neerslagoverschot (P-ET_{ref}) in het groeiseizoen (1 april-30 september) tegen de wateraanvoer voor een RDS-systeem met een vast crestniveau (A) en voor een RDS-systeem met een dynamische sturing van het crestniveau en wateraanvoer (B). Ontleend aan De Wit et al. (2024b).

Hydrologische veranderingen door opschaling RDS

De watervraag op regionale schaal stijgt als op meerdere percelen RDS-systemen tegelijkertijd water gebruiken. Oppervlaktewater is vaak beperkt beschikbaar, waardoor de uitdaging is om water evenwichtig te gebruiken en te beheren, zowel voor de verschillende gebruikers als ook voor de natuur. In een regionale analyse voor Stegeren is de regionale watervraag van RDS-systemen beschreven met het waterallocatiemodel WEAP (Terink et al., 2022). De watervraag per perceel kan dalen als in aangrenzende percelen ook subirrigatie plaatsvindt. Daarnaast is onderzocht wat de regionale hydrologische effecten van het opschalen van RDS zijn met een systeemdynamisch model (SDM) in Vensim.

Hydrologische modellen variëren van gedetailleerde, ruimtelijke modellen tot globale black-boxmodellen. Ertussenin ligt een 'lumped' SDM-model; een benadering die veel wordt toegepast om niet-lineair gedrag van complexe systemen met daarin feedbacks te begrijpen. In deze studie is een relatief eenvoudig regionaal SDM-model opgezet voor opschaling van RDS (De Wit et al., 2026). Het model bevat alle belangrijke aspecten en feedbackloops vaan een RDS-systeem en is gebaseerd op kennis van de uitgevoerde veldproeven en SWAP-modellering. Het model bevat drie belangrijke interacties: i) interactie oppervlaktewater en grondwater, ii) interactie grondwater en onverzadigde zone, iii) regionaal beheer door regionale aanvoer van oppervlaktewater en stuwpeilbeheer. Deze interacties zijn belangrijk omdat subirrigatie ervoor zorgt dat de afvoer naar de sloot toeneemt (niveauverschil tussen grondwater en oppervlaktewater neemt toe), terwijl onttrekking van oppervlaktewater voor subirrigatie het slootpeil kan verlagen, wat ook de afvoer naar de sloot versterkt. Zodra het slootpeil te laag wordt door overmatige onttrekking, is er minder water beschikbaar voor subirrigatie, wat uiteindelijk gevolgen heeft voor het effect van subirrigatie op de gewasverdamping. In dit model is het areaal waarop RDS in een gebied wordt toegepast opgeschaald in procenten van een totaal gebied. Opschaling van subirrigatie laat over het algemeen drie toestanden zien, geïllustreerd aan de hand van een specifieke situatie voor 2018 voor een gebied binnen Waterschap Limburg (Figuur 6): 1) er is voldoende oppervlaktewater beschikbaar om RDS op te schalen (tot 20% van het totale gebied voor deze specifieke situatie), waarbij het oppervlaktewaterniveau op peil blijft, 2) er is voldoende oppervlaktewater beschikbaar om

RDS op te schalen naar 30%, maar het slootpeil daalt sterk door de grotere watervraag, wat invloed heeft op de regionale waterbeschikbaarheid en de benodigde hoeveelheid water voor subirrigatie verhoogt, en 3) er is onvoldoende oppervlaktewater beschikbaar om RDS op te schalen van 30% naar 99%, omdat het waterpeil in de sloot te ver daalt, wat een negatieve impact heeft op zowel de regionale waterbeschikbaarheid als de beschikbaarheid van water voor subirrigatie en hiermee gewasgroei. Doordat de capaciteit van het regionale water is bereikt, daalt het beschikbare water per RDS-systeem (subirrigatie) bij toename van RDS-systemen, resulterend in een daling van evapotranspiratie, wegzijging en slootdrainage per RDS-systeem.



Figuur 6: Verandering in hydrologische fluxen als gevolg van opschaling van subirrigatie in een gebied: wateraanvoer voor subirrigatie, evapotranspiratie ET_{act}, wegzijging en slootdrainage. Veranderingen (met/zonder subirrigatie) en verandering in slootniveau (maximum/minimum slootniveau) zijn berekend met een op processen gebaseerde lumped SDM-model en gegeven als functie van het percentuele areaal met subirrigatie t.o.v. het totale areaal. Ontleend aan De Wit et al. (2026).

Het totale areaal dat subirrigatie kan toepassen hangt sterk samen met de totale regionale hoeveelheid wateraanvoer, het regionaal stuwpeil, maar ook de drainageweerstand. Een hogere regionale wateraanvoer en/of hoger regionaal stuwpeil resulteert in een hogere oppervlaktewaterbeschikbaarheid, waardoor er meer subirrigatie toegepast kan worden. Een hogere drainageweerstand zorgt ervoor dat er relatief meer grondwater wordt vastgehouden, minder aanvoer voor subirrigatie nodig is en er meer oppervlaktewater beschikbaar blijft. Oftewel: RDS kan bijdragen aan de waterbeheerstrategie op regionale schaal, maar verhoogt ook de druk op het oppervlaktewater, dat veelal niet onbeperkt beschikbaar is. Het SDM-model kan gebruikt worden om te verkennen of RDS opgeschaald kan worden in een gebied (met specifieke geohydrologische karakteristieken en regionaal waterbeheer) en gebruikt worden als hulpmiddel in beleidskeuzes van waterbeheerders.

De eenvoud en transparantie van het model kan ook het inzicht in de kansen en knelpunten van RDS bij zowel beleidsmakers als agrariërs vergroten.

Beheer en onderhoud van het systeem

Bewust beheer en onderhoud is cruciaal om de beschreven hydrologische effecten van RDS te behalen. In het ontwerp, aanleg en beheer van RDS moet rekening gehouden worden met de watersamenstelling van de bron van subirrigatie om verstopping te voorkomen. De bron van subirrigatie kan oppervlaktewater zijn (Smith et al., 1985), water uit bassins (Drury et al., 1996), gerecycled drainagewater (Allred et al., 2003), grondwater (Bartholomeus et al., 2018a) of behandeld (industrieel of huishoudelijk) restwater (Bartholomeus et al., 2017; Bartholomeus et al., 2018b; Narain-Ford et al., 2020). Verstoppingen kunnen bijvoorbeeld veroorzaakt worden door slootvuil in het filter van de pomp bij oppervlaktewater, maar drains kunnen ook verstopt raken door ijzerneerslag bij infiltratie met zuurstofloos, ijzerrijk grondwater. Daarnaast kunnen hoge biologische activiteit en voedingsstoffen in restwater verstopping met biofilms veroorzaken. Verstopte drains kunnen worden door gespoten, maar hierop zijn RDS-systemen veelal niet ontworpen. Om dit wel mogelijk te maken, is in de veldproef in America een voorziening getroffen om de drains toegankelijk te maken voor een spuitlans (Figuur 7). De Wit et al. (2023a) beschrijven het beheer en risico op verstopping uitgebreid.

Ook is het belangrijk dat RDS-systemen goed bediend worden door de agrariër en dat er voldoende afstemming is met het beheer door het waterschap. Alleen dan kan een verbetering van de landbouwwatervoorziening behaald worden.

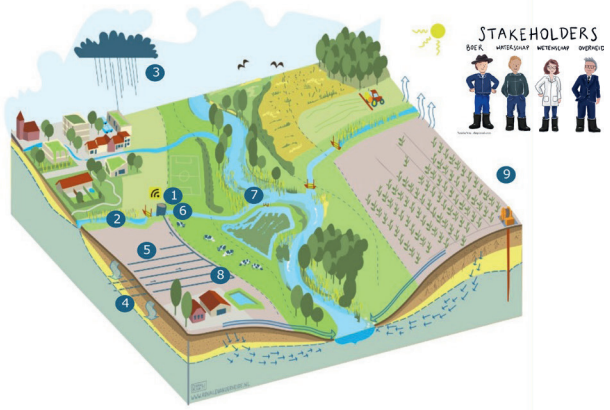


Figuur 7: Verstopping met ijzer (links), geïnstalleerde kruisstukken (midden) en een doorspuitstuk (rechts) voor de veldproef in America. Ontleend aan De Wit et al. (2023a).

Belangrijkste handvatten RDS

De opgedane kennis in de verschillende veldproeven en modelstudies leidt tot een aantal praktische handvatten (Figuur 8), zoals beschreven in De Wit et al. (2024a):

1. **Pompontwerp:** het pompontwerp wordt voornamelijk bepaald door het beoogd waterniveau in de regelput en de methode van wateraanvoer.
2. **Hydrologische kenmerken:** overtollige drainage naar de sloot kan voorkomen worden als het slootniveau het beoogde grondwaterniveau volgt.
3. **Meteorologische kenmerken:** het beheer van regelbare drainage met subirrigatie hangt sterk samen met het weer (nattere/drogere perioden in het groeiseizoen).
4. **Geohydrologische kenmerken:** de aanwezigheid van een weerstand in de bodem (vb. een leemlaag of een relatief hoog regionaal grondwaterniveau) beperkt wegzijging.
5. **Gewaskarakteristieken:** de benodigde hoeveelheid wateraanvoer is voor een gewas met een grotere worteldiepte kleiner dan voor een gewas met ondiepere wortels. Daarmee is RDS ook meer geschikt voor dieper wortelende gewassen.
6. **Waterbron – lokaal:** een waterbron van voldoende kwaliteit moet beschikbaar zijn voor subirrigatie. Dit voorkomt een eventuele verstopping van het systeem, en handhaaft de kwaliteit van het (diepere) grondwater.
7. **Waterbron – regionaal:** de waterbron moet op regionale schaal niet zijn functie verliezen als bron voor andere doeleinden (watervraag en waterverdeling).
8. **Beheer en onderhoud:** ijzerneerslag kan een drain verstoppen bij gebruik van zuurstofloos, ijzerrijk grondwater. Restwater of oppervlaktewater met veel voedingsstoffen kunnen zorgen voor verstopping door biofilms. Met goed ontwerp, aanleg en beheer van het systeem kan verstopping (deels) worden voorkomen.
9. **Belanghebbenden (stakeholders):** het is belangrijk dat zowel het waterschap als de agrariër begrijpen hoe RDS doorwerkt in het regionale watersysteem en in hoeverre de opschaling van RDS dus gefaciliteerd kan worden.



Figuur 8: Overzicht belangrijkste handvatten voor de implementatie van RDS weergegeven van 1 t/m 9. De basisfiguur is ontleend aan www.stowa.nl/lumbricus.

Conclusies

Regelbare drainage met subirrigatie (RDS) is een manier om water vast te houden, water af te voeren en grondwater aan te vullen. Aanvullen is in beginsel bedoeld voor het vergroten van de waterbeschikbaarheid van gewassen (‘ondergrondse irrigatie’ of ‘omgekeerde beregening’), maar kan ook bijdragen aan de regionale grondwateraanvulling. RDS is daarmee een technische maatregel om te anticiperen op de onbalans tussen watervraag en wateraanbod in grondwaterafhankelijke regio’s. RDS heeft drie doelen: i) water afvoeren wanneer nodig, ii) water vasthouden op het perceel om onnodige drainage te voorkomen en iii) (grond)water aanvullen. Subirrigatie vereist een zoetwaterbron in de omgeving én een lokale hydrologische situatie die geschikt is voor subirrigatie.

Als gevolg van toepassing van subirrigatie via RDS op een geschikte locatie voor subirrigatie stijgt de freatische grondwaterstand, waardoor het bodemvochtgehalte stijgt via capillaire opstijging. Hierdoor stijgt de waterbeschikbaarheid voor het gewas en hiermee de transpiratie (gewasverdamping) en de drogestofproductie. Een beperkt deel van het aangevoerde water komt echter maar ten goede aan het gewas. Afhankelijk van het oppervlaktewaterniveau en de geohydrologische gebiedskenmerken, stroomt een deel van het aangevoerde water naar de aanliggende sloot en stroomt een deel via wegzijging naar het diepere grondwater.

Als er continu water wordt aangevoerd, kan dit variëren tussen de 500 en 1000 mm per jaar. De wateraanvoer kan verminderd worden door slimmer water aan te voeren op basis van een algoritme gebaseerd op actuele vochtcondities en de weersvoorspelling. Desalniettemin vraagt een RDS-systeem wateraanvoer voor subirrigatie, waardoor deze lokale maatregel effect heeft op het regionale watersysteem. Het is daarom belangrijk dat verschillende belanghebbenden van het watersysteem afspraken maken in hoeverre RDS toegepast kan worden. Het opgezette SDM kan hierbij helpen. Als laatste factor is het beheer van een drainagesysteem cruciaal. Bij ontwerp, aanleg en beheer van een RDS moet rekening worden gehouden met de watersamenstelling van de bron van subirrigatie om verstopping te voorkomen.

De lokale maatregel RDS kan een onderdeel zijn van de regionale waterbeheerstrategie voor het verbeteren van de balans tussen watervraag en wateraanbod. Op korte termijn is het ‘laaghangend fruit’ om in ieder geval traditionele drainagesystemen om te vormen tot regelbare drainagesystemen. Afhankelijk van de geschiktheid van de locatie en regionale beschikbaarheid van water voor infiltratie kunnen systemen worden uitgebreid tot RDS. Op langere termijn kan RDS een technische maatregel zijn in landbouwgebieden, waar bodem en water leidend zijn geweest in landgebruik, om droogte- en zuurstofstress te mitigeren. Daarbij is het belangrijk rekening te houden met de eerder genoemde negen handvatten, zoals locatiegeschiktheid, regionaal oppervlaktewaterbeheer en gewaskeuze. RDS kan dan een dubbel doel dienen: het verbeteren van de gewasvochtvoorziening en het verhogen van grondwateraanvulling. Deze meerjarige studie, waarvan onderdelen zijn gepubliceerd in zowel rapporten als wetenschappelijke artikelen, heeft de kennisbasis over RDS verhoogd en kan bijdragen aan besluitvorming door agrariërs en waterschappen over de implementatie van RDS-systemen als maatregel.

Field work impressions

















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"If you want to go fast, go alone. If you want to go far, go together" – African proverb

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Foto: Gresbuis

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About the author



Janine de Wit was born on the 30th of January 1995 in Nieuwegein, The Netherlands. After her graduation from high school (Gymnasium, combined profiles Nature and Techniek (NT) + Nature and Health (NG) at Oosterlicht College in Nieuwegein) she started her studies with Soil, Water, Atmosphere Bachelor at the Wageningen University, with a minor in Undergraduated Level Teacher Physics (in Dutch: tweedegraads bevoegdheid Natuurkunde). In the final BSc Thesis she investigated 'Misty Waters; Do numerical weather prediction models catch the fog?' In between her bachelor en master, she went to Taiwan to attend the Wetskills Water Challenge hosted by National Taiwan University. She competed in a Dutch-Taiwanese team to develop an innovative concept for the case study 'Modernizing and promoting agriculture in Taiwan' for the Taiwanese and Dutch water industry. She presented the resulting out-of-the-box solution as 'A sustainable vertical greenhouse' at the FE Water Show Exhibition in Taipei.

She continued her masters at Wageningen University in Earth and Environment, with a specialization in Hydrology and Water Resources and a minor in Meteorology and Air Quality. She spent 4 months at the Volcani Institute in Israel to write her MSc Thesis about 'Optimizing drip-irrigation scheduling of olive trees in Israel, using plant, soil and water interactions and agro-hydrological model SWAP'. After that, she spent 4 months at KWR Water Research Institute to write her MSc Internship about 'Subirrigation using groundwater - the effect of a resistive loam layer'. Besides her studies, she worked as an assistant Meteorologist at MeteoGroup in Wageningen and she developed and coordinated the online lecture series BSc Soil, Water, Atmosphere at Wageningen University. Since 2019, she works as a researcher at KWR Water Research Institute in the team Ecohydrology performing research on the availability of freshwater in the Netherlands. Since 2020, she has been a part-time PhD candidate on drainage systems at the Soil Physics and Land Management Group of Wageningen University.

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SENSE CERTIFICATE

Netherlands Research School for the
Socio-Economic and Natural Sciences of the Environment

D I P L O M A

for specialised PhD training

The Netherlands research school for the
Socio-Economic and Natural Sciences of the Environment
(SENSE) declares that

Jannigje Adriana de Wit

born on 30 January 1995, in Nieuwegein, the Netherlands

has successfully fulfilled all requirements of the
educational PhD programme of SENSE.

Wageningen, 29 May 2026

SENSE coordinator PhD education

Dr Ir Peter Vermeulen

The SENSE Director

Dr Jampel Dell'Angelo

The SENSE Research School declares that **Jannigje Adriana de Wit** has successfully fulfilled all requirements of the educational PhD programme of SENSE with a work load of 63.4 EC, including the following activities:

SENSE PhD Courses

- Environmental research in context (2021)
- Research in context activity: Multiple outreach plan based activities under the title 'Bring science from the desk into the (scientific) world' (2024)

Other PhD and Advanced MSc Courses

- HYDRUS short course + HPx course, Czech University of Life Sciences (2021)
- Working with Dynamic Soil-Crop Models – an Intensive Course, Kassel University (2023)
- Science Communication, Leiden University (2025)
- Scientific Publishing, Wageningen Graduate Schools (2021)
- Acquisition skills, KWR Water Research Institute/In-zicht (2022)
- Scientific Integrity, Wageningen Graduate Schools (2023)
- Scientific Writing, Wageningen Graduate Schools (2023)
- Reviewing a Scientific Manuscript, Wageningen Graduate Schools (2023)
- MediaTraining, Big Easy/ KWR Water Research Institute (2021)
- Visual Thinking, CLASP Visuals (2021)
- Communication with the Media and the General Public, Wageningen Graduate Schools (2021)
- Making Impact: Increasing the relevance of research through science-society interaction, Wageningen Graduate Schools (2024)

Societal impact and Science communication activities

- Multiple presentations for stakeholder (2021-2025)
- Diversity of activities related to science communication, including interviews in professional journals, newspapers, national TV and podcasts (2019-2025)

Selection of Management and Didactic Skills Training

- Board member KWR Early Career (2019-2024)
- Administrator/ coordinator fieldwork room within KWR (2019-2024)
- Supervising two MSc students with thesis (2020-2022)

Selection of Oral Presentations

- *Controlled drainage with subirrigation: A management measure to discharge, retain and recharge fresh water*. Soil and water conservation under changing climate in Northern or high-altitude conditions, 04-06 May 2022, Ås, Norway
- *Circular Economy: Taking stock of waste(water)*. IWA World Water Congress, 11 – 15 September 2022, Copenhagen, Denmark
- *Hydrological consequences of controlled drainage with subirrigation*. EGU General Assembly, 23–28 April 2023, Vienna, Austria
- *Controlled drainage with subirrigation: automatic control to manage fresh water*. Netherlands Earth Sciences Conference, 7 March 2024, Utrecht, Nederland

Colophon

This work is partly based on knowledge obtained within the joint research programmes Water in the Circular Economy (WiCE, https://www.kwrwater.nl/en/samenwerkingen/collectief-onderzoek-water-circulaire-economie/), Lumbricus (https://www.stowa.nl/lumbricus), Klimaatadaptatie in de Praktijk (KLIMAP, https://www.klimap.nl/), AquaConnect and the FARMWISE project funded by the EU in the Horizon Europe framework program (grant agreement 101135533).

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