

Performance of controlled drainage in tile-drained agricultural fields: An exploratory scenario analysis with the soil-plant model SWAP

Erika Rodríguez-Lache^{a,*}, Guillaume Blanchy^{b,c}, Ali Mehmandoostkotlar^a, Sarah Garré^a

^a Flanders Research Institute for Agriculture, Fisheries and Food (ILVO), Mellebeke, Belgium

^b University of Liège (ULiège), Liège, Belgium

^c F.R.S-FNRS (Fonds de la Recherche Scientifique), Brussels, Belgium

ARTICLE INFO

Handling Editor - Brent Clothier

Keywords:

Controlled drainage
Climate-adaptive drainage
SWAP
Water management
Drainage management
Climate change adaptation
Subsurface drains

ABSTRACT

Regular drainage (RD) systems ensure optimal crop growth by preventing oxygen stress and lead to a significant loss of fresh water, a valuable resource that could be used to sustain crops during summer months. Controlled drainage (CD) systems can raise the water table above the subsurface drains using a control pit. However, it remains unclear to which extent CD contributes to better crop yield and more groundwater recharge. While manual controlled drainage (MCD) is managed by hand, climate-adaptive drainage (CAD) offers the possibility to continually adjust the water table based on weather forecast and crop needs. In this work, we conducted an *in silico* experiment using the SWAP model to investigate the interactions between drainage types (RD and MCD) over a 30-year timeframe, 3 soil textures and different drainage management practices in maize cultivation. MCD leads to an increase in groundwater recharge (between 28 % and 45 %) and it reduces the drainage flux (between 25 % and 17 %) compared to RD. MCD increases maize transpiration mostly in loamy sand soils (+ 0.5 % median). In other soils, transpiration is reduced due to oxygen stress. CAD for the 30-year data did not result in large improvements in crop transpiration and resulted in less groundwater recharge and more drainage than MCD. Although both MCD and CAD offer only minimal improvement of crop transpiration and is highly dependent on soil type, weather conditions and drainage management, they do result in enhanced groundwater recharge, which is crucial for maintaining water availability and supporting ecological systems.

1. Introduction

Water management is crucial to optimize agricultural productivity and mitigate damage related to either excessive soil moisture or water scarcity. Insufficient water supply leads to water stress (drought) and crop failure (Liu et al., 2011), whereas excessive water leads to oxygen stress and increases the susceptibility of soils to compaction (Nawaz et al., 2013). Compaction leads the soil structure to deteriorate, which in turn hinders root penetration, slows plant growth and reduces yield (Bartholomeus et al., 2008; Kaur et al., 2020). To prevent suboptimal conditions due to excessive soil moisture, drainage systems are commonly used to artificially lower water levels and improve soil conditions in diverse agricultural landscapes (Bartholomeus et al., 2023).

Tile regular drainage systems (RD) intercept and redirect surplus water by minimizing surface runoff in the agricultural landscape, preventing root anoxia and reducing erosion risk. These benefits ensure

favorable conditions for crop growth and field trafficability for the farmer (Miller et al., 2022; Molden et al., 2007). Regular tile drainage systems are primarily designed to efficiently remove excess water from agricultural fields. This leads to a reduction in the capacity of the landscape to retain and store water, which is crucial to overcome long dry periods (Ekwunife and Madramootoo, 2023). Additionally, RD may remove considerable amounts of groundwater from the water system in periods in which there is no direct agronomic or societal need for drainage. Therefore, these regular drainage systems do not offer the possibility to manage the drainage level dynamically throughout the year, but alternatives are available.

Managed drainage systems, commonly known as controlled drainage (CD), offer a tailored and dynamic approach to water management (Youssef et al., 2023). Using a hydraulic control structure placed at the end of the tile drainage infrastructure (Miller et al., 2022), this drainage technique enables farmers to adjust drainage levels according to specific

* Corresponding author.

E-mail address: erika.lucia.rodriguez@kuleuven.be (E. Rodríguez-Lache).

<https://doi.org/10.1016/j.agwat.2025.109973>

Received 20 January 2025; Received in revised form 13 June 2025; Accepted 6 November 2025

Available online 15 November 2025

0378-3774/© 2025 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

crop requirements and prevailing climate conditions (De Wit et al., 2022; Singh et al., 2022). Manual controlled drainage (MCD) is primarily used when the control structures are operated manually, while climate adaptive drainage (CAD) when the level is automatically adjusted. In CAD, the drainage level is set based on the estimated crop water requirements determined by either simple decision rules, sensors, complex soil-plant-atmosphere models or weather predictions (De Wit et al., 2024b; Miller et al., 2022). Both MCD and CAD drainage alternatives provide opportunities to increase water use efficiency, as more water and nutrients can be retained in the soil for crops (Castellano et al., 2019; Rietra et al., 2022). Most studies have emphasized the importance of CD in the reduction of drainage discharge and nutrient leaching (Miller et al., 2022; Wang et al., 2020). For instance, Kęsicka et al. (2022) demonstrated that CD allowed the accumulation of 22 kg of $\text{NO}_3\text{-N}$ per hectare. In addition, CD helps to maintain freshwater lenses on top of saline groundwater (Li et al., 2018; Pauw et al., 2015). A recent meta-analysis of 64 observations conducted primarily in North America (Singh et al., 2022) investigated the impact of controlled drainage on soil moisture during the summer season. Their results showed a mostly neutral effect of CD, primarily due to the limited amount of data reported specifically related to soil moisture depth of these measurements, which can vary significantly.

Crop transpiration is an important indicator for assessing the impact of controlled drainage in the hydrological fluxes. CD increases grass transpiration by 22 mm/year (De Wit et al., 2024b), while for soybean and maize the improvement in evapotranspiration is 27 mm/year (Youssef et al., 2018). The effects on crop yield remain ambiguous, with some studies reporting increases and some reporting no significant changes (Wang et al., 2020; Youssef et al., 2023). For instance, Wang et al. (2020) observed a slight increase in crop yield by 0.11 % due to CD in their meta-analysis over 61 publications mainly in North America and Asia. Their study also provided compelling evidence that controlled drainage effectively reduces drainage discharge.

The effectiveness of controlled drainage varies according to soil type, weather conditions, cropping systems, and control practices such as timing and imposed levels. Different soil types exhibit distinct water flow characteristics which in turn influence the reaction of MCD and CAD. For example, sandy soils commonly have better infiltration rates and lower water-conserving capacities (Sloan et al., 2016). While this results in a faster reaction to changes in the imposed drainage level, it also reduces the natural buffering capacity. In addition, soil water flow and drainage efficiency are not only affected by soil texture, but also by soil structure. An extreme example of this is the difference between ripened and unripened clays (Vermeulen et al., 2003). Finally, the architecture of the soil profile with the properties of its different horizons is crucial. For the application of CD to have agronomic benefits, the presence of an impervious layer beneath the drains is important to prevent too large percolation losses (van Bakel et al., 2013; Yu et al., 2020) and ensure the capacity to store water above the drainage level (Dukes et al., 2003).

Weather conditions also play an important role in the performance of CD systems. Factors such as rainfall intensity and duration, evapotranspiration demand, and seasonal variations in water availability have an impact on the drainage effectiveness (Salla et al., 2022; Sojka et al., 2020). Regions with irregular rainfall patterns and prolonged dry periods can benefit from CD systems because they spread the available water over longer time periods (Liu et al., 2011). In Belgium, where recharge typically happens during winter, controlled drainage systems might be beneficial during dry periods. This happens because MCD and CAD retain water in the field longer instead of discharging it immediately to a network of ditches towards the sea (as it is the case in the reclaimed coastal areas called the polders). However, it remains unclear how it affects crop performance and groundwater recharge, and how this depends on all the influencing factors: weather, soil, hydrogeology, crop and the drainage management itself. As stated before, most studies have demonstrated the effectiveness of controlled drainage in reducing

the tile nutrient and drainage discharge. However, there are only a few studies (e.g., De Wit et al., 2024a) that quantify the effects on the entire water budget and crop development. In addition, setting up and monitoring long-term experiments in various controlled drainage situations is challenging (Kęsicka et al., 2022). In order to test the effectiveness of different types of drainages for different pedo-climatic conditions and weather scenarios, while having total control on the water balance, we present a scenario-based *in silico* experiment in this paper using the SWAP (Soil–Water–Atmosphere–Plant) model (Kroes et al., 2017).

The objective here is to systematically analyze the performance of controlled drainage crop transpiration, groundwater recharge and pipe drainage. While crop transpiration is not directly proportional to crop yield because crop yield counts for only the harvestable product (Mulder et al., 2018), the usage of crop transpiration instead of crop yield allows to compare with other components of the water balance, such as pipe drainage and groundwater recharge. The analysis is developed under several realistic environmental conditions (soil, hydrogeology), distinct management options (drainage timing and levels) and weather variability. More specifically, we evaluated two crucial aspects for farmers and water managers: the impact of manual controlled drainage (MCD) on crop transpiration (direct, economic value) and on groundwater recharge and drainage flux (indirect, societal value) as compared to regular drainage (RD). We also explore the added value of climate-adaptive drainage (CAD). We do this in situations relevant for Flanders (Belgium) and for maize as example crop. For simplicity, this research focuses on the effect of MCD and CAD in the hydrological water balance and does not address the effect on nutrient leaching.

To encourage reuse and reproducibility, we provided open user-friendly Python codes (see Data and Code availability section), enabling potential users to adopt a similar strategy for other cases.

2. Materials and methods

2.1. Concept of the *in silico* approach of this paper

To analyze the impact of manual controlled drainage on the soil water budget and on crop performance in the context of Flanders, Belgium, we adopted an *in silico* approach using the 1-D soil-plant-atmosphere model SWAP (see Sections 2.2, 2.1 Fig. 1a). The *in silico* term comes from computer science and refers to a computational simulations used to plan and optimize real experiments or to explore a large range of model scenarios. *In silico* experiments provide insights on how systems respond to different conditions and give guidelines on which parameters should be measured (Benes et al., 2020). In our scenario cases, we compare manual controlled drainage (MCD) with regular drainage (RD). Regular drainage has a constant drainage level, meaning that water is continuously draining when the groundwater level in the field is higher than the water level in the discharge medium (ditch). In contrast, MCD allows farmers to adjust the drainage level manually depending on the agricultural need. In addition, we illustrate the potential of managing automatically the drainage level as considered in climate adaptive drainage (CAD) (2.3). As manual controlled drainage systems should have a sufficiently high success rate under variable weather conditions over the years to be worth the investment of money and time, we quantified its performance for a 30-year data set (1994–2023) for the area of Uccle, Belgium. We developed scenarios for maize representing combinations of a set of factors driving the drainage performance: soil texture, hydrogeological bottom boundary conditions and management of drainage (Fig. 1b).

We selected maize for all simulations because it is one of the most important arable crops in Belgium (Gobin et al., 2023; Heuvelmans, 2010). We considered two possible sowing dates: 15 April and 15 May with subsequent growing period of 160 days. These sowing dates were selected to represent a reasonable potential range for sowing maize in Belgium (Estrella et al., 2022; Gobin et al., 2023). Different crops like sugar beet or winter wheat have different rooting depths, which would

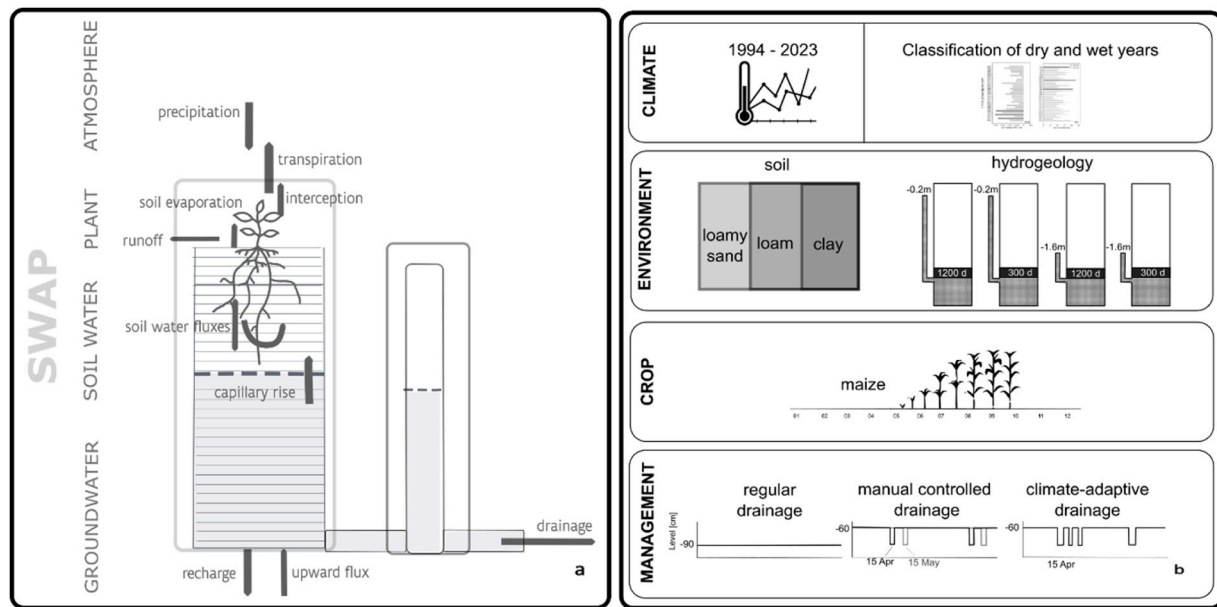


Fig. 1. (a) SWAP model showing the different fluxes (b) In silico approach employed in this research with its different components: climate data, crop, environment (soil type and hydrogeology) and management. The onset of manual controlled drainage (MCD) -0.6 m occurs on April and May, while for climate adaptive drainage (CAD) on April.

certainly affect the management of the groundwater table. The effect of soil type is illustrated using three contrasting textures: loamy sand, loam and clay characterized by the hydraulic parameters from the Rosetta database (U.S. Department of Agriculture, 2019). This database has been validated in several regions (Schaap et al., 2001; Stumpp et al., 2009).

Because the options for water retention and percolation from the soil profile are strongly driven by the hydrogeology defined at the bottom boundary condition, we designed four contrasting scenarios illustrating the effect of the aquitard resistance (i.e. the hydraulic conductivity of the layer below the soil profile) and the effect of the pressure head of the underlying aquifer (see 2.4). In this study recharge is defined as the water flux through the bottom boundary downwards, while the opposite is referred to as upward flux. The four different bottom boundary scenarios may result in either recharge or upward flux through the bottom boundary. The magnitude and direction of this water flux is critical for controlled drainage. In the upward flux situation, a drainage level closer to the surface can still retain a great deal of water in the field, even after precipitation stops.

Drainage management options were set as follows. Regular drainage is implemented with a drainage base of -0.9 m below ground surface as is common in Flanders. This value was selected based on expert knowledge, insights from drainage companies and local farmers since the drainage base in Flanders ranges from -0.8 to -1.1 m. For manual controlled drainage, the high drainage level during retention phases was fixed at -0.6 m with a low drainage level of -0.9 m for sowing and harvesting. The high drainage level was determined from literature where optimal groundwater levels (GWL) for maize range between -0.5 and -1 m (Heuvelmans, 2010; Zipper et al., 2015). This choice is arbitrary, as optimal levels vary together with all other factors. However, in order to compare between years and disentangle the contribution of different effects, this was the most straightforward yet realistic setup. In the MCD scenarios, the low water level of -0.9 m was applied 10 days before sowing and 10 days before harvest as is commonly necessary to ensure trafficability on the field (Ekwunife and Madramootoo, 2023; Miller et al., 2022).

We assumed that it was always possible to release water from the field to the ditch, thereby ignoring possible effects of ditch water level on the drainage system (i.e. subirrigation from the ditch to the field) as is common in ditches managed by the local Water Board (for instance, in

the Flemish Polders). To evaluate the performance of MCD compared to RD over the 30-year period, a paired *t*-test was applied (Hsu and Lachenbruch, 2014). Both MCD and RD were assumed to be dependent treatments as they were performed under the same weather conditions each year. Paired *t*-test were performed under the different combinations of soil texture, water fluxes (drainage, recharge and transpiration) and controlled pit management scenarios. In the paired *t*-test, the mean water flux differences between MCD and RD were calculated for each combination. *p*-values are considered significant below 0.05.

2.2. Numerical modeling using SWAP

The Soil Water Atmosphere Plant (SWAP) (Kroes et al., 2017) model v4.2.0 is a one-dimensional hydrological model which solves the Richards (1931) equation using a finite difference approach (Fig. 1a). The required input data include soil hydraulic properties, top boundary conditions driven by the weather, crop parameters, drainage system properties and bottom boundary conditions (De Wit et al., 2024b). SWAP has been developed and tested for more than 50 years in the Netherlands (Heinen et al., 2024) under similar weather, hydrogeological conditions and management practices as in Flanders. Therefore, the model appears appropriate for exploring a range of drainage scenarios in Flanders.

To represent maize transpiration, we used the static or “simple” crop module of SWAP. This module considers that the green canopy and the rooting depth do not depend on climatic conditions (Kroes et al., 2017). The dynamic crop module (WOFOST) (De Wit et al., 2020) was not considered in this study as it requires more parameters that were not always available. Furthermore, estimating these parameters would have potentially increased the uncertainty on the model outputs. As we first wanted to focus on the drainage section, we used the simple crop module as a way to minimize uncertainty coming from the above-ground part. This simple crop module has been used for several conditions all over the world (Monaco et al., 2014), thus we considered it acceptable for our simulations. ‘Crop transpiration’ refers to transpiration at the canopy scale. The potential evapotranspiration is calculated using the Penman Monteith equation, from which the transpiration is derived via crop height (crop and aerodynamic resistance). In addition, the model assumes that crop transpiration is equal to the root water uptake,

neglecting water accumulation in the plant (Kroes et al., 2017). The water uptake under optimal and drought conditions was simulated by the Feddes et al. (1976) function. Under dry conditions, the Feddes function describes how the root water uptake decreases linearly between two soil matric potential values. We used the approach of Bartholomeus et al. (2008) to calculate water uptake in oxygen deficient conditions. Compared to the traditional Feddes approach for oxygen reduction, Bartholomeus et al. (2008) calculates the daily transpiration based on physiological (root and microbial respiration) and physical process (oxygen diffusion) (Heinen et al., 2024). The Jarvis (2011) root water compensation was included in this study to represent the transpiration process. This compensation considers the potential of the plant to alleviate stress in a part of the root zone by increasing uptake in another zone. The root water uptake is incorporated in the Richards equation as a sink term.

The drainage flux q_{drain} sink term is calculated by the head difference between groundwater and drainage system divided by drainage resistance (Eq. 1) where Φ_{avg} is the averaged phreatic groundwater level midway between the drains (cm), Φ_{drain} is the drainage level including imposed levels such as -0.6 m or -0.9 m and Υ_{drain} is the drainage resistance in days (Xu et al., 2012). The drainage resistance is situation specific, but for the present scenario analysis it remained constant for all simulated cases. Following the approach of Tebbens et al. (1999), we estimated that a drainage resistance of 12 days was appropriate for typical Belgian farmland.

$$q_{\text{drain}} = \frac{\Phi_{\text{avg}} - \Phi_{\text{drain}}}{\Upsilon_{\text{drain}}} \quad (1)$$

The simulations were conducted independently for each period, which spanned from the end of August in the year preceding the growing season year until the end of December of the following year, covering a total of 485 days. This approach facilitated the comparison of the influence of climate on soil water balance consistently across all years, without considering the impact of previous events and initial soil moisture conditions at the beginning of the simulations. As a result, the memory effect of subsequent droughts on groundwater tables over multiple years is not accounted for in this analysis. To maintain a focus on the water balance, we chose transpiration instead of crop yield as an indicator of crop performance. Table S.1 provides a comprehensive overview of the modeling parameters used in this study.

2.3. Implementation of climate-adaptive drainage

Climate-adaptive drainage (CAD) describes forms of automated controlled drainage where the timing and duration of the drainage is continuously adjusted to the weather conditions and soil water status of the parcel in question (van den Eertwegh et al., 2015). To adapt the drainage level to the climate, data on groundwater level in the parcel and weather predictions are necessary. While a manual controlled drainage system requires more human labor to adjust the drainage level at the control pit, CAD requires a motorized control since the frequency of operation increases. Such systems with remote control can cost more than 10k€ (Van den Eertwegh and Droogers, 2013) and demand yearly maintenance. To help potential users assess the costs and benefits of both systems, we assessed improvements to agronomic performance and water budget of CAD in comparison to MCD. We selected the loam soil type along the 30-year period using a fairly simple automated drainage program: if the water level rises above a maximum threshold (i.e. -0.6 m below surface level or -0.3 m above the tile drains placed at -0.9 m) the control pit opens completely for two consecutive days. Then the drainage level is reset to the targeted water level of -0.6 m. It is possible to further optimize the automation based on data from soil water potential sensors and/or crop modeling, but that exceeds the scope of this article.

2.4. Formulation and analysis of the bottom boundary conditions representing contrasting hydrogeological contexts

In this study, a flux type bottom boundary condition was used (Eq. 2). The bottom flux q_{bot} (cm/day) is calculated from difference of the hydraulic head in the phreatic groundwater Φ_{aquif} (cm) and an average hydraulic head in an underlying semi-confined aquifer Φ_{avg} (cm) divided by its aquitard resistance C (day). This Cauchy bottom boundary condition is commonly used in SWAP simulations where drainage systems are involved (e.g. De Wit et al. 2024b and Faúndez Urbina et al. 2020). It allows us to represent different realistic scenarios regarding the provision of water to the soil-plant system from below and the speed with which water can reach the bottom of the soil system.

$$q_{\text{bot}} = \frac{\Phi_{\text{aquif}} - \Phi_{\text{avg}}}{C} \quad (2)$$

Since this boundary condition type highly influences the dynamics of the water table and the amount of water retained in the soil profile, we illustrate how the hydraulic head in the confined aquifer (AQAVE parameter in SWAP) and the aquitard resistance C (RIMLAY parameter in SWAP) influence the performance of MCD. To address this, we generated four scenarios in loam soil representing all combinations of AQAVE values of -0.2 and -1.6 m and RIMLAY values of 1200 and 300 days as depicted schematically in (Fig. 1b) the interaction between the top and bottom boundary conditions, the tuning of the parameters AQAVE and RIMLAY were developed over a 30-year period with April 15 as drainage/sowing date.

Fig. 2 shows the impact of these four parameter combinations on soil moisture profile in the beginning (1 May) and towards the end (1 August) of the maize growing season. On 1 May, all the parameter combinations result in a water content close to saturation above the drains installed at -0.9 m, except for the low RIMLAY of 300 days and low AQAVE of -1.6 m. Low RIMLAY and low AQAVE result in a high recharge flux through the lower boundary causing the reduction of water content above the drains, which is not the case for MCD at the beginning of growing season. High AQAVE of -0.2 m and a low RIMLAY of 300 days maintains the water content close to saturation at the imposed water level -0.6 m for both 1 May and 1 August throughout the entire growing season. High ground water levels are rarely observed in late summer except within a system with a significant upward flux from an underlying aquifer or during intense long periods of rainfall. When comparing low (-1.6 m) and high (-0.2 m) AQAVE using high RIMLAY (1200 days), the outcomes in water content remain similar at the beginning of the crop season. However, in most years by late summer (1 August), a gradual shift towards the residual water content in all soil textures is observed when low AQAVE (-1.6 m) is applied. This shift change is commonly observed, especially in the top layers, as MCD cannot retain enough water until the end of the season. Additionally, in 1 August, a zone of water depletion in the upper -0.3 m for all years is observed after rain events; this can be explained primarily by root water uptake.

These outcomes confirm that the hydrogeological conditions at the bottom of the drained soil-plant system strongly influence the dynamics of the water table and therefore the performance of MCD. These results regarding the boundary conditions suggests that the parameter combination of high RIMLAY of 1200 days and low AQAVE of -1.6 m is the most suitable option to represent controlled drainage in SWAP, as they follow common hydrogeology and weather conditions for Flanders. This parameter set was therefore chosen for the both controlled drainage analysis MCD and CAD discussed below.

2.5. Meteorological analysis and selection of wet and dry years

A 30-year (1994 – 2023) dataset of historical daily weather from Uccle, Belgium (Joint Research Centre, 2024) was used as an input for the SWAP model. Climate predictions were not included. To account for

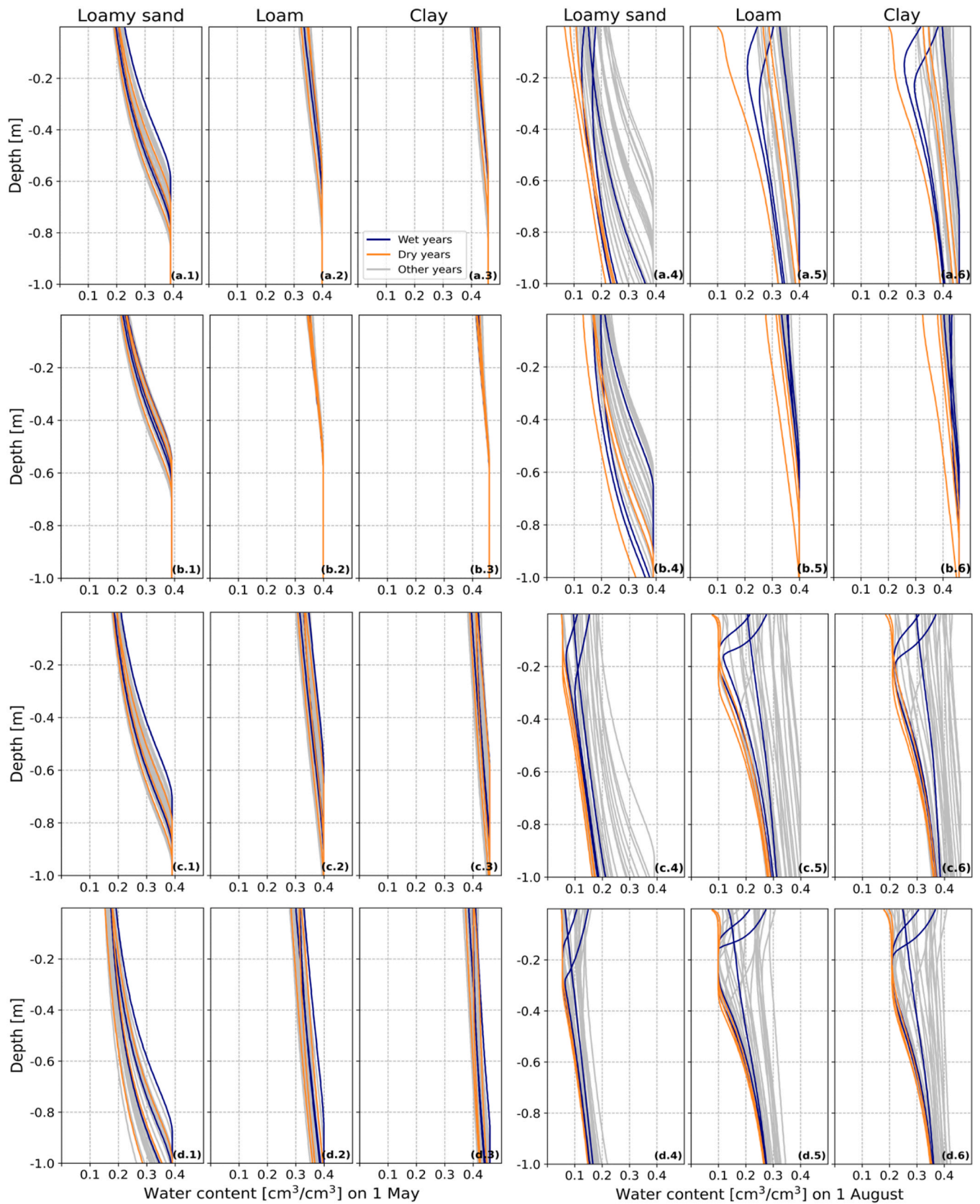


Fig. 2. Effect of manual controlled drainage (MCD) on soil moisture content using different values for the hydraulic head in the confined aquifer (AQAVE in m) and the aquitard resistance (RIMLAY in days) for a 30-year dataset. The water content is shown for 1 May and 1 August for loamy sand, loam and clay soils using different combination of: (a) RIMLAY = 1200 and AQAVE = -0.2, (b) RIMLAY = 300 and AQAVE = -0.2, (c) RIMLAY = 1200 and AQAVE = -1.6, (d) RIMLAY = 300 and AQAVE = -1.6. Blue and orange lines represent the wet years (1994, 2001, 2006) and dry years (2018, 2020, 2022), respectively.

the increased likelihood of climatic extremes in Flanders due to climate change, we identified those extremes in the historical dataset to illustrate the effect of extreme conditions on the performance of MCD and CAD. The definition of dry and wet years was based on two metrics, the precipitation deficit index (PDI) and the number of consecutive days with rainfall (CDR). The PDI is the difference between daily precipitation and the reference evapotranspiration (Bayissa et al., 2018; Vanon-geval and Gobin, 2023). For CDR, a day is classified as a rainy day as soon as a threshold of 0.2 mm of rainfall is reached, as implemented by Gobin and de Vyver (2021). Both meteorological indices (PDI and CDR) were calculated for the duration of a typical growing season for maize in Flanders, i.e. from 15 April to 10 September (160 days in total). Per each year, the cumulative PDI was computed for the entire growing season, whereas the maximum CDR was selected. As crop growth and performance depend not only on the extent of a dry or wet period, but also the timing of those events in the growing season, we repeated the calculation of the indices separately for each of the three main stages in the maize growing season (BBCH 2001): vegetative, reproductive and maturity stage. In Belgium, the vegetative, formation and maturity stages for maize last approximately 55, 36 and 65 days, respectively

(personal communication with agronomic experts). We selected the three driest and three wettest years of the 30-year dataset as they represent the most extreme weather cases and cover 10 % of the data. Fig. 3 shows the calculated metrics in the three growth stages and over the entire season. Negative PDI values (precipitation lower than reference evapotranspiration) are predominant. The years 2020, 2018 and 2022 have the smallest PDI and were selected as ‘dry’ years. The PDI distribution across the main BBCH growing stages reveals that years with positive PDI occur more frequently as the growing stage advances. In the maturity stage, five years out of ten show a positive precipitation deficit index, meaning there is more precipitation available than the evaporative demand. The years 2001, 1994 and 2006 all had more than 20 consecutive rainfall days during the growing season and were thus selected as wet years. For these years, the highest number of CDR occurred during the maturity stage. Some years were hard to classify as wet or dry. For instance, in 2023, the maximum number of consecutive dry and wet days were 22 and 18, respectively. In that year, dry circumstances characterized the vegetative stage, followed by wet conditions during the formation stage.

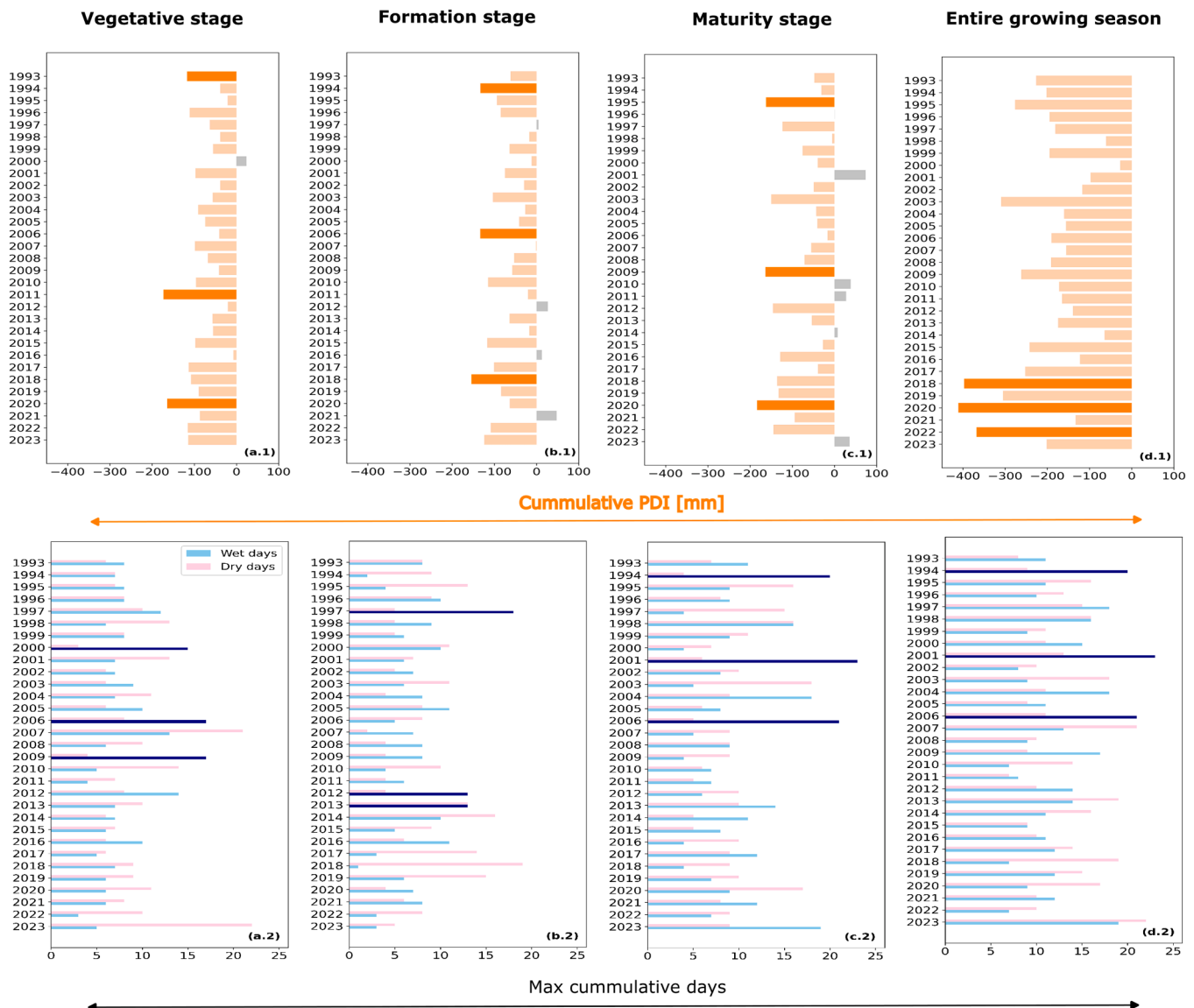


Fig. 3. (top) Cumulative precipitation deficit index (PDI) for 30 years in different growing stages (a) to (c) and during the entire growing season (d). (bottom) Maximum cumulative days with rainfall (blue) and without rainfall (red) for 30 years. Darker orange and blue years represent the three extreme wet and dry years.

3. Results

3.1. Time series of fluxes and relevant variables during the dry year 2020

Fig. 4 shows the main fluxes in (rainfall) and out (transpiration, drainage) of the soil-plant system as simulated using SWAP during the dry year 2020 together with some relevant variables: oxygen and dry stress, groundwater level, soil matric potential (PHEAD variable in SWAP) and rooting depth. It contains the scenarios in which maize was sown on 15 April in loam soil. Fig. 4 illustrates how the scenarios are implemented and the impact they have on those fluxes and variables over time. In 2020, drainage only occurs in winter due to the excessive rainfall and the high groundwater level above the imposed MCD and RD levels of -0.6 and -0.9 m, respectively. In winter during intense precipitation events, the maximum drainage discharge peaks were not different between MCD and RD. However, the drainage flux decreases faster under MCD than under RD. Under MCD, the cumulative discharge

drops by 19 % compared to RD over the entire simulation period. In this dry year, a bit of oxygen stress occurs in the beginning of the growing season, followed by a period dominated by dry stress. This is also visible in the soil pressure head (higher incidence of negative values towards the end of the growing season). Groundwater levels decrease as a consequence of both rainfall reduction and the drainage management at the start of the growing season, but differences between MCD and RD disappear over time, even in the dry year 2020. Over the simulation period, the groundwater level increases by 8.5 % using MCD compared to RD. In 2020, lowering the drainage level for harvest is not effective, as GWL levels have dropped below the deepest drainage level by that time. In MCD, no significant increase in transpiration was simulated in 2020 as compared to RD. Additionally there is no meaningful difference (0.05 %) in soil evaporation between MCD and RD (data not shown).

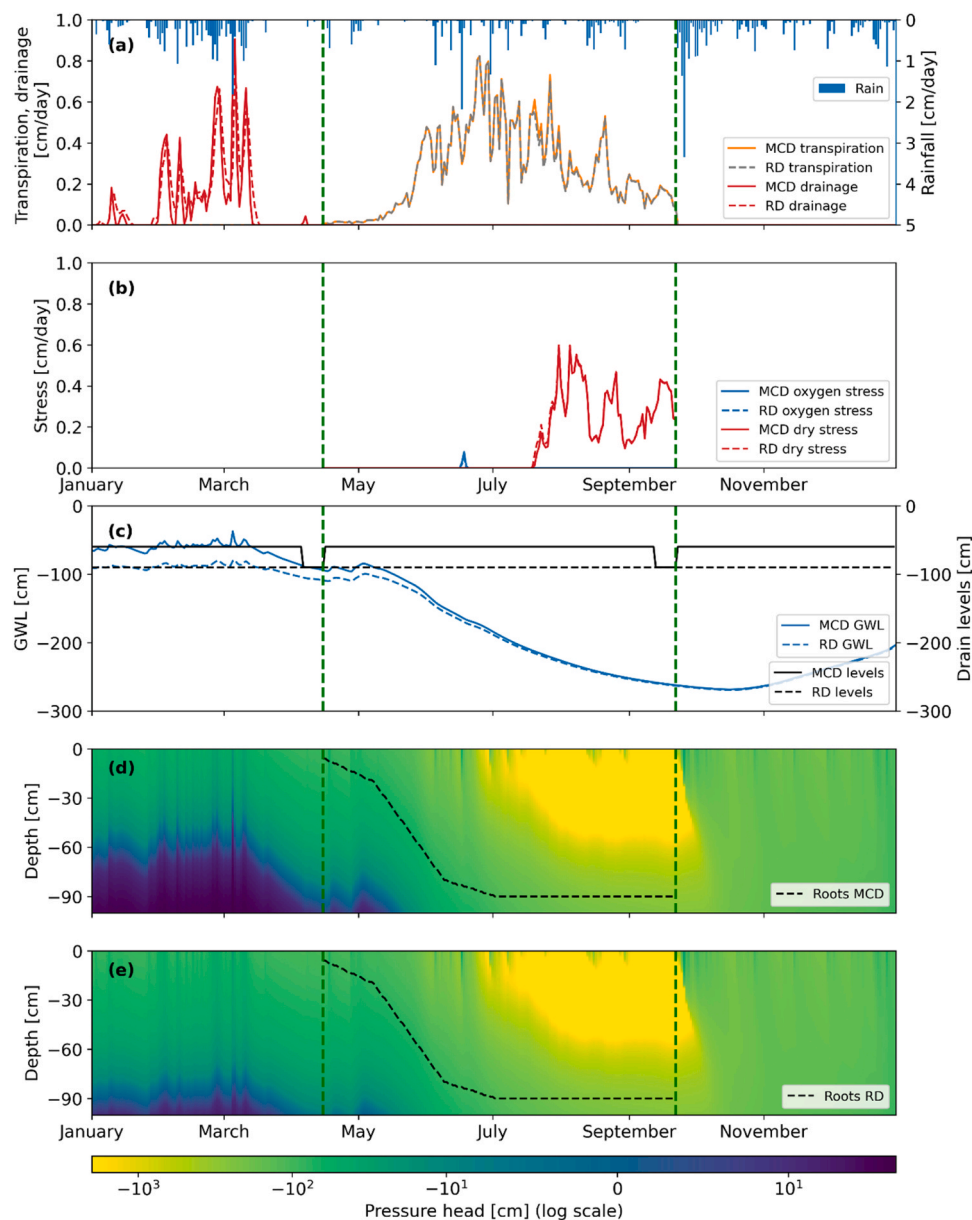


Fig. 4. Simulation results for manual controlled drainage (MCD) and regular drainage (RD) during the 2020 dry year. (a) water fluxes (transpiration, drainage & rainfall), (b) oxygen and dry stresses, (c) groundwater levels (GWL) and drain levels, pressure head in logarithmic scale and rooting depth for (d) MCD and (e) RD. The green dashed lines represent the planting and harvesting dates for maize.

3.2. Influence of soil texture on the performance of controlled drainage

Soil texture significantly influences the distribution and movement of water along the soil profile and therefore also the effectiveness of drainage practices. Fig. 5 shows how soil texture affects the difference between MCD and RD for the most important fluxes of the water balance. We calculated this for the 30-year time series (1994–2023) for three soil textures (loamy sand, loam, clay) and focusing on the scenario in which the water level is lowered in the control pit on 15 April. Fig. 5 displays the average difference between MCD and RD in average flux cumulated over the growing season. Positive values represent an increase in the respective water flux due to manual controlled drainage, while negative values represent a decrease. The larger the bar, the bigger the difference between MCD and RD; in other words, the more effective manual controlled drainage was in reducing or increasing that specific flux. It does not say anything about the absolute magnitude of that flux (Fig. 6).

The additional amount of water percolating (recharge) at the bottom of the soil profile due to MCD remains nearly constant across all soil types, with median values between 4.2 and 4.6 cm cumulating over the entire year. However, the drainage flux is strongly affected by soil texture. The differences are negative for this flux for all soil textures, showing that MCD is effective to reduce the amount of water lost by drainage as compared to RD. The median reduction is bigger in loamy sand compared to loam or clay, with values of 5.7 cm and 4.6 cm, respectively. Loamy sand soil is most reactive to drainage management (higher hydraulic conductivity). Note that in extremely dry years such as 2018 and 2020, the drainage flux is strongly reduced both in RD and MCD, removing the effect of soil texture (Fig. 8). The median transpiration is higher under MCD than under RD for loamy sand only. On the finer soil textures, oxygen stress is occurring more frequently resulting in lower transpiration across the 30 years. One must mention that there are outliers in which the transpiration also increases for the finer textures (Fig. 8). For instance, in 2018, transpiration in MCD increases by 0.97 % and 1.15 % for loam and clay soils.

3.3. Drainage management: effect of timing, frequency and duration on water fluxes and crop transpiration

Installing a control pit is only a first step; optimizing the operation is equally important. As optimal management varies with all other factors studied above, simulations are crucial to explore the effect of drainage timing (and by extension full climate-adaptive drainage) on crop performance and on the water balance. For two management practices

(sowing on 15 April and 15 May) in loam soil, we calculated the impact of MCD on the total transpiration, drainage and recharge fluxes for all 30 years from 1994 to 2023 (Fig. 6). Because most drainage and recharge occur during the winter in Flanders, these calculations were performed for 1) the entire simulation period and 2) the maize growing season alone. When counting only the growing season, the median cumulated drainage and recharge were both below 5 cm, while over the entire simulation period, the recharge is greater than 10 cm while drainage is more than 21 cm.

MCD retains more water in the soil than RD, regardless of sowing date/timing of the controlled drainage events. As a result, MCD allows more water to percolate into the underlying aquifer. For the sowing date 15 April, the median recharge increases by 4 cm over the entire simulation period, while sowing date 15 May results in a recharge increase of 6 cm. MCD significantly reduces the amount of drainage by 4 and 5 cm for sowing dates 15 April and 15 May, respectively. Interestingly, the tendency toward increased recharge and decreased drainage under MCD is greater for sowing on 15 May. Even though most of the contribution to each water flux happens during winter, rainfall events late in the summer and/or beginning of fall can contribute to these water fluxes in spite of the intense evapotranspiration during the growing season. Note that RD also results in changes to drainage and recharge fluxes with the sowing date. In the RD scenario, the drainage base remains constant, but the timing and magnitude of transpiration still varies with the sowing date due to a different growing period.

In manual controlled drainage, the 30-year median data show a slight decrease in crop transpiration compared to regular drainage. This outcome is consistent across both controlled management practices; it is most likely due to the additional oxygen stress as MCD increases the amount of water in the root zone.

Fig. 7 highlights how varying weather conditions influence the effect of manual controlled drainage. It illustrates the effect of MCD on dry and oxygen stress in the three most extremely wet and dry years in loam soil (2.5). MCD reduces dry stress compared to RD irrespective of the timing of lowering the water level to prepare for sowing. This positive effect is more pronounced during wet years and early sowing (15 April) as more water can be stored in the root zone. During these wet years, MCD reduces dry stress by only 1.76 cm. Interestingly, in the selected dry years, maize sown in April reported significantly more dry stress compared to maize sown in May, with values of 18.15 cm and 8.06 cm, respectively.

Even if dry stress can be partially mitigated by MCD, the increases in oxygen stress might be problematic. Regardless of the timing of water level management, oxygen stress increases with MCD. Overall, these results suggest that extreme weather conditions during the growing season strongly influence the dynamics of the root water uptake.

The goal of controlled drainage is not only to reduce crop stress and improve transpiration but also to reduce the quick evacuation of water from the landscape. Fig. 8 shows that controlled drainage indeed always diminishes the amount of water drained from the system and increases the groundwater recharge towards the lower aquifer. However, its effect on crop transpiration depends strongly on the soil texture, weather conditions and whether the drainage management was appropriately implemented to mitigate both drought conditions as well as oxygen stress. Our *in silico* approach makes it possible to evaluate the complex interaction between soil texture, drainage management, weather conditions and crop growth. We performed a paired *t*-test between MCD and RD during the 30-year period and for all discussed scenarios for each of the studied fluxes of the water balance to assess whether they were statistically different under MCD than under RD. (Table S2 provides the statistical results of the paired *t*-test). The results indicated that there was a statistically significant difference (*p*-value < 0.05) between the median of both MCD and RD in all combinations except for transpiration in loamy sand soil under MCD with a sowing date/timing of 15 May.

The results of the combination of all factors discussed above (soil texture, weather, sowing/timing management) are summarized in Fig. 8. This figure presents the annual increase in water flux (in %) for

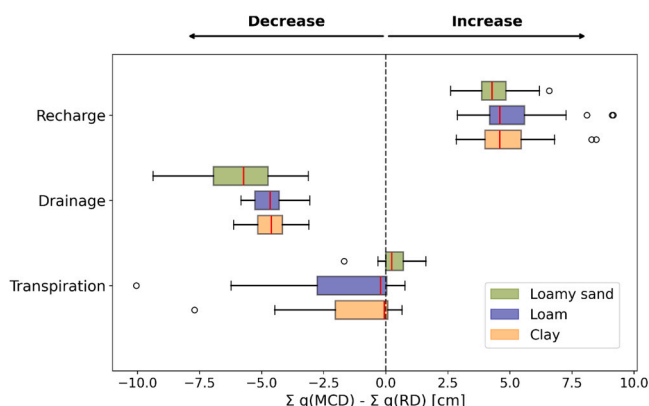


Fig. 5. Difference between the cumulative water fluxes between manual controlled drainage (MCD) and regular drainage (RD) over the growing season for different soils (loamy sand, loam and clay) along the 30-year time series using a sowing date of 15 April. Each box represents the distribution of MCD – RD differences per year, with the red line indicating the median value for each water flux.

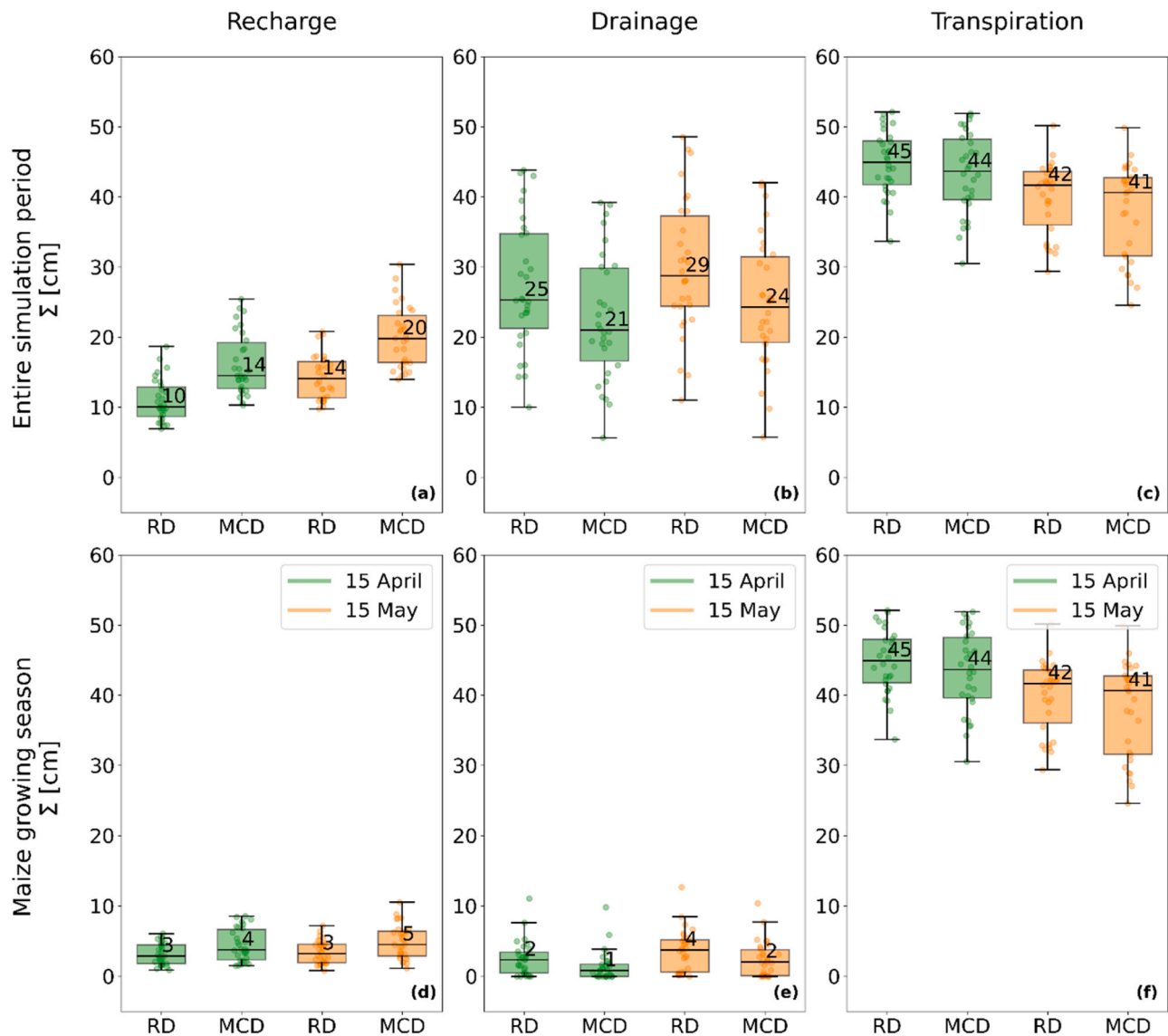


Fig. 6. water fluxes for regular drainage (RD) and manual controlled drainage (MCD) using two controlled pit managements: 15 April and 15 May in loam soil. The results are shown for 30 years for the simulation of the entire year (a, b, c) and the growing season (d, e, f). Each box represents the yearly distribution with the horizontal line indicating the median of each water flux under a specific sowing/drainage management.

MCD compared to RD. A positive value indicates a rise in the water flux due to MCD compared to RD. MCD increases recharge to the underlying aquifer in all years of the 30-year dataset. This median increase is approximately 28 % for coarser and 45 % for finer soils, averaged across both April and May sowing/drainage management. Under MCD, drainage was reduced (around 18 %) for loam and clay soils independent of drainage timing. This reduction was higher for loamy sand (22–26 %). Earlier drainage (April) slightly increases the median transpiration (by 0.5 %) in loamy sand soil across the 30-year timeframe. However, the year by year analysis shows that the soil texture strongly determines in how many years an improved transpiration is occurring: 19 years for loamy sand, 9 years for loam, and 12 years for clay soil in the case of sowing on 15 April and associated drainage immediately before sowing.

Given the impact of drainage timing on crop transpiration and other water fluxes, climate adaptive drainage (CAD) using an automated control pit and groundwater level and/or soil moisture sensors may present a solution to optimize oxygen and dry stresses during the season, while still retaining more water in the landscape than in regular drainage. To investigate this, we implemented a simple form of CAD

along the 30-year time series in which the drainage level is lowered as soon as a desired threshold of groundwater level is reached, i.e. -0.6 m below ground surface. The CAD system lowered it to the pipe level (-0.9 m) for two days before returning it to the target level (-0.6 m). This is a simple form of CAD, as the drainage level itself can also be adjusted dynamically to obtain optimal soil moisture conditions in the root zone adapted to the crop growth. Because that solution requires more sensors and model predictions and the goal was to investigate the value of CAD, we opted for the simple CAD solution. The simulations were performed using loam soil type and with the maize sowing date of 15 April. Fig. 9 represents the comparison of groundwater levels and water stresses (oxygen and dry) between dynamic controlled drainage and regular drainage during the wet years of 2001 and 2006. 2001 was a wet season along the maturity stage, while 2006 during the vegetative stage (2.5). The CAD was activated three times in 2001 and four times in 2006, of which the first and last were before sowing and harvest, identical to MCD. This shows that CAD is activated more often when there are precipitation days at the beginning of the growing season as the groundwater table is closer to the surface. However, these high groundwater levels lead to oxygen stress as seen in 2006. In contrast, in

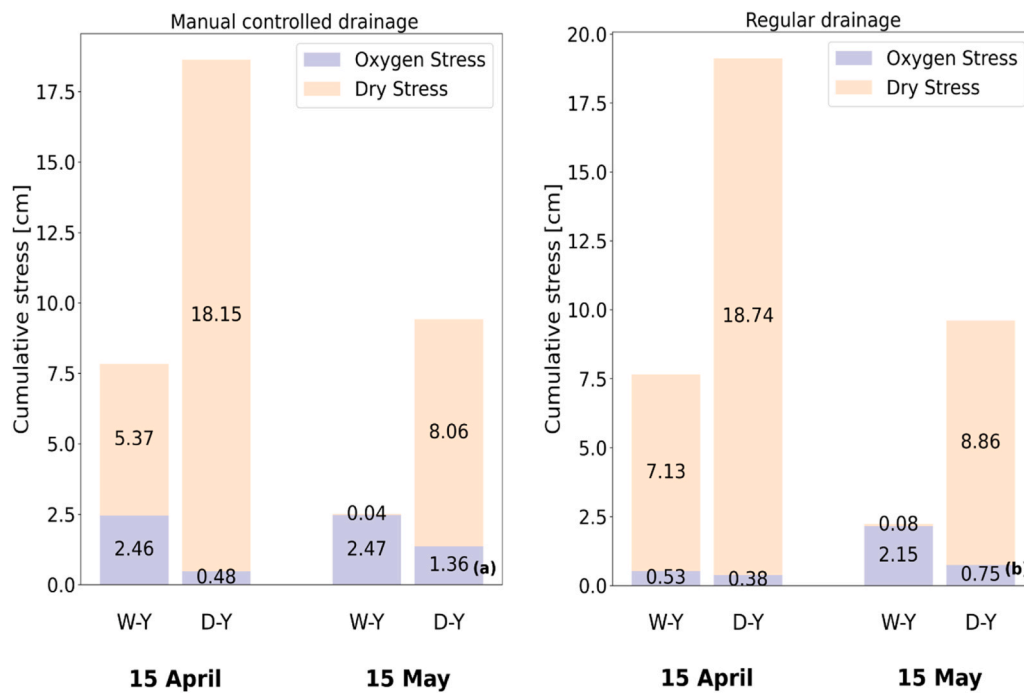


Fig. 7. Influence of the different controlled drainage management of 15 April and 15 of May on oxygen and dry crop stresses. This impact is shown for manual controlled drainage (a) and for regular drainage (b) along the growing period. These stress accounting is analyzed in the three most prominent wet year years (W-Y) and dry years (D-Y).

extremely dry years such as 2020, the water level never reached the threshold of -0.6 m. As a result, CAD was not activated on any day during the growing season in that year. This indicates that in intense drought growing seasons CAD did not add value compared to MCD (data not shown). Model results along the 30-year period (Fig. 10) showed that the recharge was reduced by 0.4 cm compared to MCD. The year 2007 presented the highest recharge reduction with a value of 2.03 cm. Drainage pipe increased 0.7 cm compared to MCD along the 30-years, being the 2007 with the highest increment. Even though crop transpiration was not higher for CAD compared to MCD considering all years, CAD increases transpiration, particularly in wet years. For instance, in 2006, there was an increase of 0.22 cm using CAD since the dry stress is mitigated at the end of the growing season.

4. Discussion

4.1. Modelling manual controlled drainage: reliability and constraints

The effects of controlled drainage on the water balance fluxes have not received as much research attention as their impact on the quantity and quality of drainage water (Singh et al., 2022; Wang et al., 2020). The limited exploration of this aspect might be attributed to the high cost of experimentation and the limitations of many field-scale computational models in accurately simulating soil-plant processes coupled with drainage (De Wit et al., 2022; Ritzema and Stuyt, 2015; Van de Craats et al., 2021). Salo et al. (2021) have shown that the 2D numerical soil-plant system coupled to a 3D subsurface model (the FLUSH model) is reasonably reliable to represent the fluxes within a drained soil-plant system using a data set from Finland, although that is a quite computationally expensive approach with a high number of parameters to define. De Wit et al. (2024b) have calibrated the quasi-2D numerical model SWAP to represent controlled drainage and subirrigation in 4 experimental sites in the Netherlands with satisfying results. While the existing models require further validation in a larger variety of pedoclimatic and hydrogeological contexts to accurately quantify the actual flow magnitudes within the system, they have already proven to be

reasonably reliable to test the effect of different water management scenarios. The results of the current scenario analysis for the context of Flanders, Belgium can therefore serve as a basis for further controlled drainage research, targeting the validation of the highlighted tendencies and knowledge gaps from the scenario analysis.

4.2. Environmental benefits of MCD in the water balance components

The *in silico* experiments consistently demonstrate that manual controlled drainage systems have a notable impact on hydrological and environmental goals primarily by reducing drainage outflows and increasing groundwater recharge. Our simulations covering the period from 1994 to 2023 demonstrate that pipe drainage is reduced by approximately 22 %. This coincides with 160 studies around the globe in which average pipe drainage was reduced by 28 % compared to regular drainage (Wang et al., 2020). Using DRAINMOD, Youssef et al. (2021) demonstrated that the majority of these reductions might be attributed to the increase of lateral flow from the saturated zone in a shallower sandy soil layer. This SWAP simulation does not consider lateral flow from either the saturated or the unsaturated zone. The model is a quasi-2D: the water balance is represented by the vertical fluxes, just including the drainage flux in a quasi-2D approach. On sloping terrain, interflow can indeed be an important process resulting in a redistribution of water. Nevertheless, in fields under controlled drainage, the slope is commonly minimal (less than 1 %) (Yu et al., 2020), as a result, interflow is generally considered negligible. In some agricultural fields, the amount of water retained in the soil due to controlled drainage is highly affected by the ditches or streams nearby the field. To represent these interactions, it is recommended to add an extra drainage module into the SWAP model to include these surface water streams, as showed by De Wit et al. (2024b). Alternatively, the usage of a 2D or 3D model can represent these dynamics. However, it is important to considered that increasing the dimension of a model requires a higher number of parameters which are not always available. It is difficult to predict the exact amount of groundwater recharge due to the complex interaction between weather, crop, soil and hydrogeological context. Salla et al.

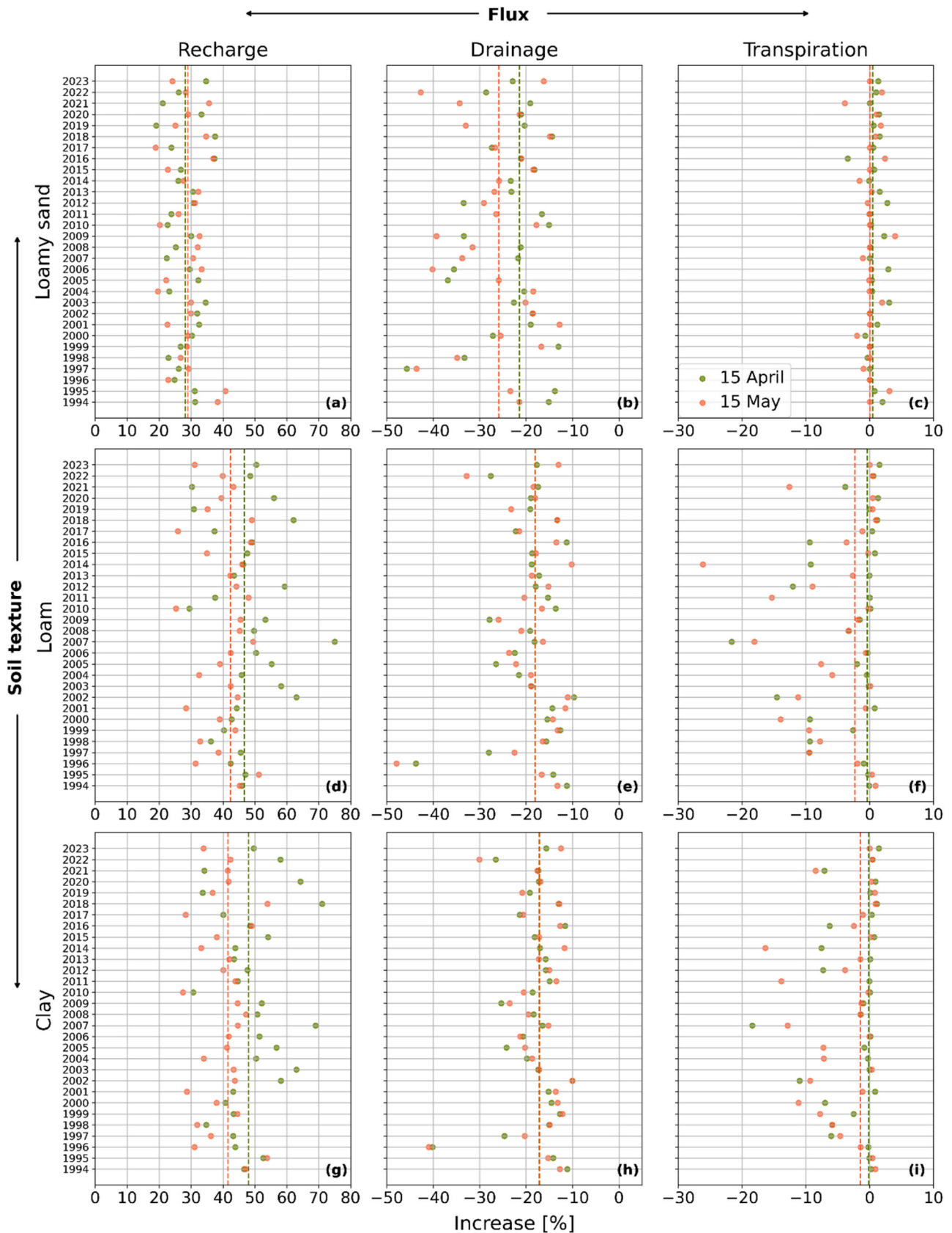


Fig. 8. Increase of the water fluxes under manual controlled drainage (MCD) compared to regular drainage (RD) in [%] for loamy sand soil (a,b,c), loam (d,e,f) and clay (g,h,i) soils. The plotted vertical lines represent the median percentage increase across all simulated years under the controlled pit management of 15 April (green line) and 15 May (red line). A positive value indicates an increase in water flux due to MCD.

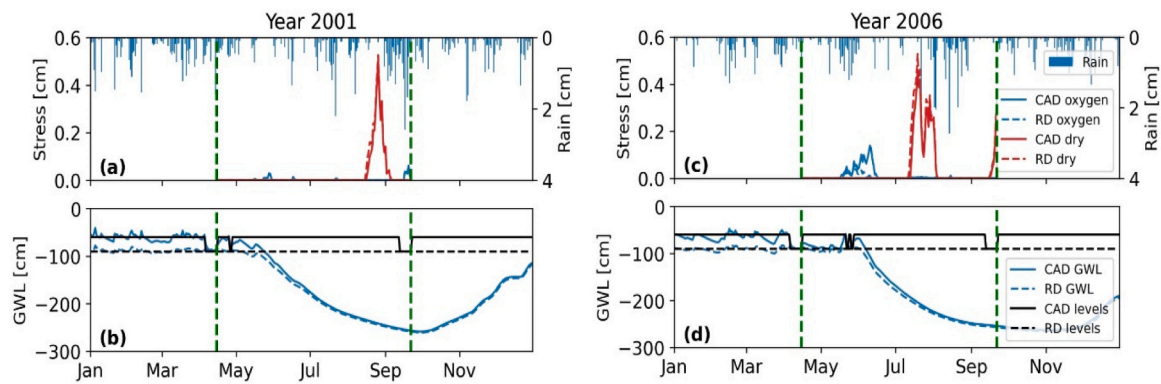


Fig. 9. Simulated dry stress, oxygen stress and groundwater levels under climate adaptative drainage (CAD) compared to regular drainage (RD) in the year 2001 (a, b) and in the year 2006 (c, d).

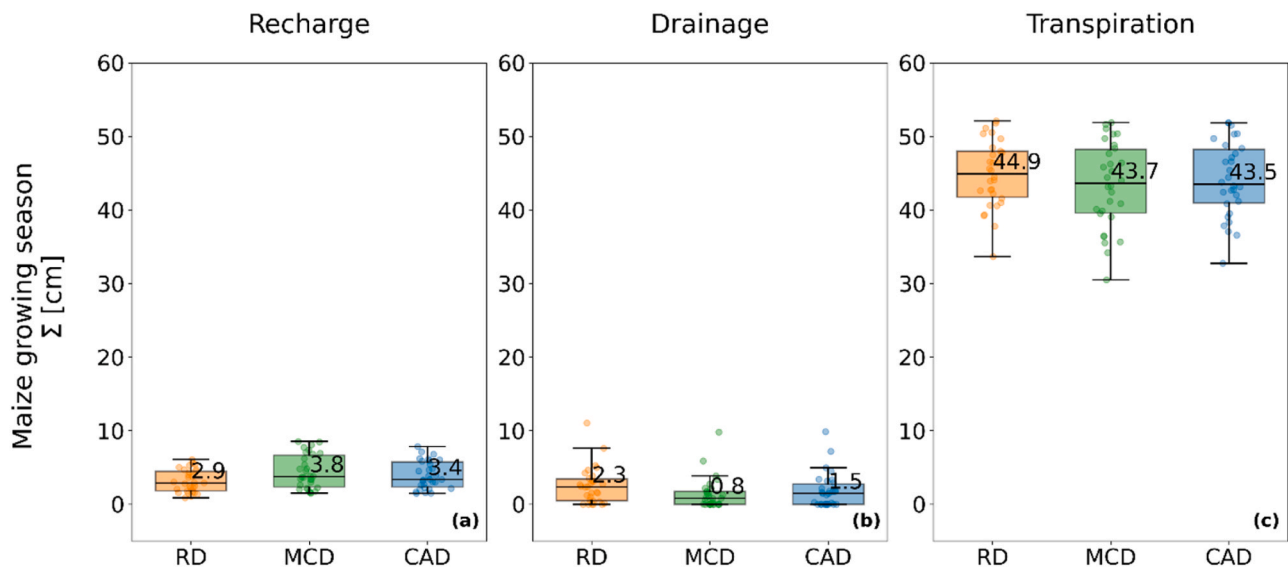


Fig. 10. water fluxes for regular drainage (RD), manual controlled drainage (MCD), and climate-adaptive drainage (CAD) along the growing season using the sowing date of 15 and loam soil. The results are shown for 30 years.

(2022) and Salo et al. (2021) demonstrate that MCD considerably increases deep groundwater recharge using unsaturated flow models, whereas Sun et al. (2016) concludes when employing a bucket water balance model that this increase is minimal compared to the effective rainfall. Our simulations suggest that MCD increases a median recharge between 28 % and 45 % compared to RD in the Flemish pedoclimatic context.

4.3. Agronomic impacts and crop response

Although it is widely hypothesized that manual controlled drainage improves crop development, the scenario analysis shows that this is far from universal. From our simulations, we observed a moderate median increase in crop transpiration only in loamy sand soils over 30 years and a decrease in other soil types. While crop transpiration is related to crop biomass, it does not directly relate to yield because yield formation depends on complex source-sink relations (e.g. partitioning, respiration) and therefore more difficult to interpret. It should be noted that the agronomical outcome depends highly on the combination of weather conditions, soil characteristics and controlled drainage management. MCD mitigates dry stress, but in wet years oxygen stress increases if the water level is only managed before sowing and harvest (common practice for many farmers working with this technique). This is also

confirmed by De Wit et al. (2024a), who demonstrates that MCD reduces dry stress in grass by 22 cm in a dry year and increases oxygen stress by 0.05 cm during a wet year compared to RD using the SWAP model. In this study, we used transpiration as a proxy for crop yield (they are directly related in SWAP and can thus be compared with the other fluxes of the water balance). In the literature, crop yield is most often used to assess the effectiveness of MCD. For instance, Ekwunife and Madramootoo (2023) and Tolomino and Borin (2019) demonstrated a positive impact of MCD on maize yield during dry years, but negative impacts during wet years. In addition, five out of eight studies compiled by Youssef et al. (2023) indicate that MCD does not have a considerable effect on maize yield.

4.4. Effect of the soil texture

The effects of manual controlled drainage in achieving both environmental and agronomical goals are significantly influenced by different combinations of soil texture, drainage management practices, crop characteristics and weather conditions (Singh et al., 2022; Youssef et al., 2023). Among these factors, the frequency, magnitude and timing of dry and wet events (weather conditions) are particularly important. Soil texture highly influences the effect of MCD on the amount of water distributed in each of the fluxes, especially for drainage and

transpiration. In our study on loamy sand, loamy and clay soils, we have shown that MCD effectively reduces water loss, as it significantly decreases the drainage pipe flux compared to RD. This allows water to be stored in the root zone throughout the entire maize growing season where it can be used later, thus mitigating dry stress. In coarse soils under wet conditions, the surplus water is drained faster, thus preventing oxygen stress. Finely textured soils are more vulnerable to excess rainfall, as the water residence time increases compared to coarse soils (Wang et al., 2009). In finely textured soils, MCD leads to a decrease in maize crop transpiration due to an increase in oxygen stress. It must be noted that there are very few studies, especially in field conditions, quantifying the oxygen stress in plants and even less on how various agricultural crops cope with this and might adapt their rooting system or physiological processes. For instance, Bartholomeus (2010) has shown that the calculation of critical gas-filled porosities of the soil is essential to determinate oxygen stress caused by increase of soil moisture. It seems now that the effect of oxygen stress might sometimes be overestimated and further validation of the underlying processes in field experiments is necessary.

The drainage design was outside the scope of the present study, but the depth and spacing of the drains can be adjusted according to soil texture to optimize water availability. Yu et al. (2020) and Fouss et al. (1999) emphasize that the limitations of MCD for medium and fine soil textures are not due to physical issues but rather economic considerations. For instance, to reduce oxygen stress in MCD, design properties such as reduced pipe spacing and increased pipe diameter could lead to higher installation costs. However, regulatory guidelines often enforce farmers to place MCD systems on the existing regular drainage pipes, impeding the ability to change the pipe spacing and diameter. *In silico* simulations may reveal differences in effectiveness of MCD pipe spacing and diameter for different soil textures.

4.5. Impact of controlled level management

Decisions on timing of the drainage measurements prove to be crucial as well. Our simulations demonstrated that if the controlled water management begins early in the maize growing season (15 April), MCD is more favorable for crop development than on 15 May, since more time is left to build up the water table again with spring rain before the drier periods start and crop transpiration increases. Even though this is a simplified representation of how controlled drainage management can vary with soil properties stability and crop calendars, it shows that the timing of the operation of the control pit will also affect the efficiency of MCD. Kęsicka et al. (2023) showed that initiating the controlled drainage management earlier in spring significantly increases the number of days where the groundwater level rises above the drainage pipes. We also see in our results that this approach helps to reduce dry stress in more advanced crop development stages. Even more, we see that if we increase drainage events to alleviate oxygen stress in our CAD scenarios, the drought stress typically increases later in the season compared to MCD, since less water is retained in the system for later. Tolomio and Borin (2019) conclude that years characterized by wet springs followed by summer droughts create more favorable conditions for MCD. However, the raised groundwater table might increase oxygen stress during the earlier crop growth phases. Zipper et al. (2015) observed that the increase in groundwater level due to MCD during the vegetative stage in maize causes leaf area index (LAI) reduction due to oxygen stress but in more advanced growing stages, the LAI peak lasted longer due to more soil moisture in the root zone. Additional insights are needed to understand how crop growth and physiological changes are affected when soil moisture status is close to saturation. Models may currently underestimate the capacity of the plant to adapt to dynamic groundwater levels, both by dynamically adapting their rooting pattern and by utilizing compensation mechanisms with their root system at a specific moment in time.

To optimize agronomical outcomes, the management of manual

controlled drainage levels should be adjusted depending on the specific cultivar, groundwater level, soil texture and weather site conditions. The impact of groundwater level on maize transpiration is determined by the rooting depth and the canopy development (Ayars et al., 2006; Kang et al., 2001). For crops with deeper roots, the groundwater level should be deeper. However, since manual controlled drainage is intended for shallower groundwater levels that can be managed above the pipe drainage depth, having a deeper groundwater level is not practical. In terms of soil texture, Kang et al. (2001) demonstrate that the optimal groundwater level for maize is -1.2 m in loam soil while Zipper et al. (2015) report optimal groundwater levels of -0.6 for sandy loam, -0.8 for loam and -0.9 for silt loam soils. Farmers in Flanders typically adjust the level before going on the field, for trafficability, as shown in this scenario analysis. The extreme conditions whether too wet or too dry require the farmer to regularly adjust the water level (Giller et al., 2025). This weather variability indicates the need for a decision support system that can help farmers to make these water management decisions in a more informed way. This system could take into account local conditions, crop type, and real-time weather conditions. Doing this, the adjustment of the control level could significantly improve crop development. In our *in silico* approach, we consistently applied a MCD level of -0.6 m across all years and soil texture scenarios. This uniformity enabled us to compare how standard controlled pit management affects various water fluxes using a common MCD installation in Flanders with a drain placed at -0.9 m depth below surface. Therefore, our current results should not be interpreted as a universal guideline but rather as an example to explore the magnitude of the effect of several influencing factors on controlled drainage performance and for conditions in Flanders (Belgium). Using the Python codes, one could now easily adapt the current methodology to another combination of soil-crop-drainage design and management.

4.6. Climate adaptive drainage

Precipitation (occurrence and duration) plays an important role in the effectiveness of climate-adaptive drainage (CAD). CAD is often recommended to optimize drainage efficiency for both agronomic and environmental objectives (Youssef et al., 2023). We therefore tested a simple form of CAD in loam soil type in this study. In our 30-year period simulation, CAD was set to prevent groundwater levels above -0.6 m, which could be problematic for maize crop development as high groundwater levels leads to oxygen stress. In our 30-year data set, the median results showed that CAD did not show benefits on crop transpiration compared to MCD. However, in specific years characterized by high amount of rainfall in the early season (e.g. 2007, 2012, 2014; see rainfall analysis in Methods), CAD improved crop transpiration between 7 % and 15 %. In these years, the reduction of the groundwater drainage level to -0.9 m lowered the water content in the root zone, avoiding oxygen stress. Opposite in drier years, the water removal due to CAD reduces the water availability to cope with drought stress in more advanced crop stages. This can be problematic since the flowering in maize is the most vulnerable stage to water scarcity (Farré and Faci, 2009). In addition, because the control level using in CAD is reduced throughout the growing season, fast water fluxes such as drainage increases by 0.7 cm, while slower water fluxes such as groundwater recharge decreases by 0.4 cm. This demonstrates that in consecutive days with rainfall, CAD easily removes water from the landscape, as water is evacuated faster through the pipes and does not reach the underlying aquifer. CAD is a recent development in agricultural drainage management, thus only a few studies are available for comparison to our results. For instance, De Wit et al. (2024a) concluded that the usage of CAD decreases pipe drainage by 32.2 cm, groundwater recharge by 21.0 cm and transpiration by 0.3 cm compared to MCD with subirrigation during a wet year. The application of subirrigation for both MCD and CAD in their study explains the clear difference in the results between their study and the present one. Our findings are similar to those

of Miller et al. (2022) who demonstrate that CAD reduces annual drainage volumes compared to RD. They also conclude that for individual intense rainfall events (cumulative rainfall higher than 10 mm), no significant difference in the maximum drainage discharge is observed between CAD and RD. They conclude that the extreme precipitation events combined with antecedent wet conditions create a similar discharge pattern for both CAD and RD. Future improvements could adapt the management of CAD decision based on soil moisture conditions and rainfall patterns to maintain optimal conditions for crop growth, as demonstrated by Bartholomeus et al. (2015). The combined results of these studies demonstrate the need for additional research on CAD, because it is recognized as a drainage alternative that helps farmers adapt to the current change in weather conditions.

4.7. Bottom boundary condition sensitivity

To further understand the applicability of crop-soil water models as a representation of controlled and regular drainage, it is important to understand their characteristics and setup. Before testing our *in silico* approach, different combinations of aquitard resistance (RIMLAY) and the underlined hydraulic head (AQUAVE) were tested. Even though every site will have its own specific parameter combination to accurately represent the local field conditions, the chosen combinations in our scenario analysis enabled us to grasp the influence of these parameters on the soil water distribution and the direction of water fluxes (in and out of the system) in a context in which controlled drainage could be considered as a useful water management technique. Groundwater levels in Flanders tend to start high at the beginning of the growing season and tend to drop below the drainage level by late summer. The results indicate that a high RIMLAY value produces the impermeable layer effect beneath the pipes, which is important to reduce downward seepage and to maintain the desired groundwater level (Yu et al., 2020). De Wit et al. (2024b) demonstrated that calibrated values of RIMLAY oscillated from 350 to 2000 days whereas AQUAVE oscillated from 1.4 to 2.0 m for agricultural plots located in the Netherlands. Our selected values of RIMLAY and AQUAVE fall within those ranges, indicating that our *in silico* approach is close to in situ experiments in which MCD could be successful. These findings must be interpreted with caution, as the combination of weather, soil properties and controlled level pit management vary for different regions and situations. The present bottom boundary condition analysis provides an overview on how the parameter definition at the boundary plays an important role on the model results for controlled drainage.

5. Conclusion

The present *in silico* study suggests that manual controlled drainage (MCD) reduces pipe drainage and increases groundwater recharge to the underlying aquifers compared to regular drainage (RD). This provides a significant societal benefit by promoting sustainable groundwater management and reducing loss from agricultural landscapes. The agronomical benefit as measured by maize transpiration as a proxy for crop yield is minimal and occurs mainly when maize is cultivated in loamy sand soil and when the controlled pit management starts earlier in the season (15 April). This benefit is influenced by the following factors: (I) the site-conditions (soil characteristics, groundwater level) of each field, (II) controlled pit management (timing and level) and (III) weather conditions (wet and dry). The different combination of these conditions plays an important role in the distribution and amount of the water flux in the soil. For instance, in wet years, more water can be retained in the landscape using MCD by maintaining a high level in the controlled pit, especially in fine texture soils. This may result in more oxygen stress and a concomitant reduction in crop transpiration. Climate-adaptive drainage (CAD) simulation in loam soil showed that the societal benefits are reduced compared to MCD (i.e., CAD increases the amount of pipe drainage and reduces the groundwater recharge). On average

during the 30-year simulation, CAD did not lead to significant improvements on crop transpiration compared to MCD in loam soil. The results of this study offer valuable insights for farmers and water managers, contributing to informed policymaking on farm decision-making and supporting sustainable smart drainage techniques in agricultural systems. For future studies, it is recommended to include a more detailed representation of the dynamic rooting system under the different soil moisture dynamics caused by MCD and CAD. Since typically rotations will take place on the parcel on which the drainage control is installed, the inclusion of cover crops in the analysis would give a more realistic view on the overall impact of the technique on the farmer practice. While the hydrological management of controlled drainage is complex, this study demonstrated the inherent interdisciplinary nature of the topic. Future research combining hydrology, agronomy and farm economics will be needed to meet the challenges associated with drainage management in a changing environment.

CRediT authorship contribution statement

Guillaume Blanchy: Writing – review & editing, Software, Conceptualization. **Erika Rodríguez-Lache:** Writing – review & editing, Writing – original draft, Software, Formal analysis, Data curation, Conceptualization. **Sarah Garré:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Ali Mehmandoost-kotlar:** Writing – original draft, Software, Data curation, Conceptualization.

Funding

The research was funded by the Flemish Government through the OP-PEIL project (VLAIO HBC.2020.3159). Guillaume Blanchy is a Research Fellow of the Fonds de la Recherche Scientifique – FNRS (CR: 1.B.044.22F).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank Tom Coussement, Marthe Michielsens, Martin Mulder, Janine de Wit, Ruud Bartholomeus and Gé Van den Eertwegh for their knowledge exchange and support in the implementation of drainage in SWAP. Additionally, we thank Miriam Leversson for the English language editing.

Supplementary material

Python code and SWAP input files are available in this gitlab repository: <https://gitlab.ilvo.be/plant-modelling/oppeil-swap>.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.agwat.2025.109973](https://doi.org/10.1016/j.agwat.2025.109973).

Data availability

Data will be made available on request.

References

- Ayars, J.E., Christen, E.W., Hornbuckle, J.W., 2006. Controlled drainage for improved water management in arid regions irrigated agriculture. *Responsible Manag. Water Agric.* 86, 128–139. <https://doi.org/10.1016/j.agwat.2006.07.004>.
- van Bakel, P.J.T., van den Eertwegh, G.A.P.H., Massop, H., Brandsma, J., 2013. Landelijke geschiktheid van conventionele, samengestelde peilgestuurde en klimaataangepaste drainage, Tech. rep. FutureWater, Wageningen, The Netherlands.
- Bartholomeus, R.P., 2010. Moisture Matters: Climate-proof and process-based relationships between water, oxygen and vegetation.
- Bartholomeus, R.P., Witte, J.-P.M., van Bodegom, P.M., van Dam, J.C., Aerts, R., 2008. Critical soil conditions for oxygen stress to plant roots: substituting the Feddes-function by a process-based model. *J. Hydrol.* 360, 147–165. <https://doi.org/10.1016/j.jhydrol.2008.07.029>.
- Bartholomeus, R.P., Simons, G.W., van den Eertwegh, G.A., 2015. Anticipating on amplifying water stress: Optimal crop production supported by climate-adaptive water management. KWR.
- Bartholomeus, R.P., van der Wiel, K., van Loon, A.F., van Huijgevoort, M.H., van Vliet, M.T., Mens, M., Muurling-van Geffen, S., Wanders, N., Pot, W., 2023. Managing water across the flood-drought spectrum: experiences from and challenges for the Netherlands. *Camb. Camb. Ster* 1, e2.
- Bayissa, Y., Maskey, S., Tadesse, T., Van Andel, S.J., Moges, S., Van Griensven, A., Solomatine, D., 2018. Comparison of the performance of six drought indices in characterizing historical drought for the upper Blue Nile Basin, Ethiopia. *Geosciences* 8. <https://doi.org/10.3390/geosciences8030081>.
- Benes, B., Guan, K., Lang, M., Long, S.P., Lynch, J.P., Marshall-Colón, A., Peng, B., Schnable, J., Sweetlove, L.J., Turk, M.J., 2020. Multiscale computational models can guide experimentation and targeted measurements for crop improvement. *Plant J.* 103, 21–31.
- Castellano, M.J., Archontoulis, S.V., Helmers, M.J., Poffenbarger, H.J., Six, J., 2019. Sustainable intensification of agricultural drainage. *Nat. Sustain* 2, 914–921. <https://doi.org/10.1038/s41893-019-0393-0>.
- De Wit, A., Boogaard, H., Supit, I., van den Berg, M., 2020. System description of the WOFOST 7.2, cropping systems model. Wageningen Environmental Research.
- 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. *Agric. Water Manag.* 269, 107677. <https://doi.org/10.1016/j.agwat.2022.107677>.
- 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., 2024b. Hydrological consequences of controlled drainage with subirrigation. *J. Hydrol.* 628, 130432. <https://doi.org/10.1016/j.jhydrol.2023.130432>.
- 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., 2024a. Controlled drainage with subirrigation systems: Reduce water supply by automatic control. *Agric. Water Manag.* 303, 109022. <https://doi.org/10.1016/j.agwat.2024.109022>.
- van den Eertwegh, G., Kuipers, L., Klerk, W., van Bakel, J., Stuyt, L., van Iersel, A., Talsma, M., 2015. Klimaataangepaste drainage: middel tegen piekafvoeren en watertekorten. *H2O Tijdschr. Voor Watervoorzien. En. Afvalw.* 45, 8–10.
- Dukes, M., Evans, R., Gilliam, J., Kunickis, S., 2003. Interactive effects of controlled drainage and riparian buffers on shallow groundwater quality. *J. Irrig. Drain. Eng.* 129, 82–92.
- Ekwunife, K.C., Madramootoo, C.A., 2023. Influence of seasonal climate and water table management on corn yield and nitrous oxide emissions. *Agric. Water Manag.* 279, 108207. <https://doi.org/10.1016/j.agwat.2023.108207>.
- Estrella, D., De Swaef, T., Garré, S., Bartholomeus, R., Mulder, M., Hack-ten Broeke, M., 2022. PEILIMPACT Report.
- Farré, I., Paci, J.-M., 2009. Deficit irrigation in maize for reducing agricultural water use in a Mediterranean environment. *Agric. Water Manag.* 96, 383–394.
- Faúndez Urbina, C., van den Berg, F., van Dam, J., Tang, D., Ritsema, C., 2020. Parameter sensitivity of SWAP-PEARL models for pesticide leaching in macroporous soils. *Vadose Zone J.* 19, e20075.
- Feddes, R.A., Kowalik, P., Kolinska-Malinka, K., Zaradny, H., 1976. Simulation of field water uptake by plants using a soil water dependent root extraction function. *J. Hydrol.* 31, 13–26.
- Fouss, J.L., Evans, R.O., Belcher, H.W., 1999. Design of controlled drainage and subirrigation facilities for water table management. *Agric. Drain.* 38, 719–742.
- Giller, O., Ploegmakers, H., Meijerink, S., 2025. Reconfiguring agricultural water management practices: Lessons from research on scaling of controlled drainage and subirrigation systems. *Agric. Water Manag.* 312, 109451. <https://doi.org/10.1016/j.agwat.2025.109451>.
- Gobin, A., de Vyver, H., Van, 2021. Spatio-temporal variability of dry and wet spells and their influence on crop yields. *Agric. For. Meteorol.* 308–309, 108565. <https://doi.org/10.1016/j.agrformet.2021.108565>.
- Gobin, A., Sallah, A.-H.M., Curnel, Y., Delvoe, C., Weiss, M., Wellens, J., Piccard, I., Planchon, V., Tychon, B., Goffart, J.-P., 2023. Crop phenology modelling using proximal and satellite sensor data. *Remote Sens.* 15, 2090.
- Heinen, M., Mulder, M., van Dam, J., Bartholomeus, R., de Jong van Lier, Q., de Wit, J., de Wit, A., Hackten Broeke, M., 2024. SWAP 50 years: advances in modelling soil-water-atmosphere-plant interactions. *Agric. Water Manag.* 298, 108883. <https://doi.org/10.1016/j.agwat.2024.108883>.
- Heuvelmans, G., 2010. Development and credibility assessment of a metamodel relating water table depth to agricultural production. *Agric. Water Manag.* 97, 1731–1741. <https://doi.org/10.1016/j.agwat.2010.06.004>.
- Hsu, H., Lachenbruch, P.A., 2014. Paired t test. *Wiley StatsRef Stat. Ref. Online*.
- Jarvis, N., 2011. Simple physics-based models of compensatory plant water uptake: concepts and eco-hydrological consequences. *Hydrol. Earth Syst. Sci.* 15, 3431–3446.
- Joint Research Centre, E.C., 2024. Agri4Cast Data Portal [WWW Document]. URL <https://agri4cast.jrc.ec.europa.eu/dataportal/> (accessed 6.8.24).
- Kang, S., Zhang, F., Hu, X., Jerie, P., Zhang, L., 2001. Effects of shallow water table on capillary contribution, evapotranspiration, and crop coefficient of maize and winter wheat in a semi-arid region. *Aust. J. Agric. Res.* 52, 317–327.
- Kaur, G., Singh, G., Motavalli, P.P., Nelson, K.A., Orłowski, J.M., Golden, B.R., 2020. Impacts and management strategies for crop production in waterlogged or flooded soils: a review. *Agron. J.* 112, 1475–1501.
- Kęsicka, B., Stasik, R., Kozłowski, M., 2022. Effects of modelling studies on controlled drainage in agricultural land on reduction of outflow and nitrate losses—a meta-analysis. *Plos One* 17, e0267736.
- Kęsicka, B., Kozłowski, M., Stasik, R., 2023. Effectiveness of controlled tile drainage in reducing outflow and nitrogen at the scale of the drainage system. *Water* 15, 1814. <https://doi.org/10.3390/w15101814>.
- Kroes, J., Van Dam, J., Bartholomeus, R., Groenendijk, P., Heinen, M., Hendriks, R., Mulder, H., Supit, I., Van Walsum, P., 2017. SWAP version 4: theory description and user manual. Alterra-Rapp.-Wagening. Univ. Res. Cent.
- Kroes, J.G., van Dam, J.C., Bartholomeus, R.P., Groenendijk, P., Heinen, M., Hendriks, R. F.A., Mulder, H.M., Supit, I., van Walsum, P.E.V., 2017. SWAP version 4. Wageningen Environmental Research, Wageningen. <https://doi.org/10.18174/416321>.
- Li, S., Luo, W., Jia, Z., Tang, S., Chen, C., 2018. The pros and cons of encouraging shallow groundwater use through controlled drainage in a salt-impacted irrigation area. *Water Resour. Manag.* 32, 2475–2487.
- Liu, H.L., Yang, J.Y., Tan, C.S., Drury, C.F., Reynolds, W.D., Zhang, T.Q., Bai, Y.L., Jin, J., He, P., Hoogenboom, G., 2011. Simulating water content, crop yield and nitrate-N loss under free and controlled tile drainage with subsurface irrigation using the DSSAT model. *Agric. Water Manag.* 98, 1105–1111. <https://doi.org/10.1016/j.agwat.2011.01.017>.
- Miller, S.A., Witter, J.D., Lyon, S.W., 2022. The impact of automated drainage water management on groundwater, soil moisture, and tile outlet discharge following storm events. *Agric. Water Manag.* 272, 107828. <https://doi.org/10.1016/j.agwat.2022.107828>.
- Molden, D., Oweis, T.Y., Pasquale, S., Kijne, J.W., Hanjra, M.A., Bindraban, P.S., Bouman, B.A., Cook, S., Erenstein, O., Farahani, H., 2007. Pathways for increasing agricultural water productivity.
- Monaco, E., Bonfante, A., Alfieri, S.M., Basile, A., Menenti, M., De Lorenzi, F., 2014. Climate change, effective water use for irrigation and adaptability of maize: A case study in southern Italy. *Biosyst. Eng.* 128, 82–99.
- Mulder, H., van Bakel, P., de Vos, A., van Straten, G., Heinen, M., Kroes, J., 2018. Zouttolerantie aardappelen SWAP-WOFOST toepassing op Zilt Proefbedrijf Texel. Stowa.
- Nawaz, M.F., Bourrie, G., Trolard, F., 2013. Soil compaction impact and modelling. A review. *Agron. Sustain. Dev.* 33, 291–309.
- Pauw, P.S., van Baaren, E.S., Visser, M., de Louw, P.G., Essink, G.H.O., 2015. Ampliação da lente de água doce subjacente a crista de drenagem utilizando um sistema artificial de recarga e dreno: estudo de caso na Holanda. *Hydrogeol. J.* 23, 1415–1430.
- Richards, L.A., 1931. Capillary conduction of liquids through porous mediums. *physics* 1, 318–333.
- Rietra, R., Heinen, M., Oenema, O., 2022. A Review of Crop Husbandry and Soil Management Practices Using Meta-Analysis. *Stud. Towards SoilImprov. Crop. Syst. Land* 11, 255.
- Ritsema, H., Stuyt, L., 2015. Land drainage strategies to cope with climate change in the Netherlands. *Acta Agric. Scand. Sect. B—Soil. Plant Sci.* 65, 80–92.
- Salla, A., Salo, H., Koivusalo, H., 2022. Controlled drainage under two climate change scenarios in a flat high-latitude field. *Hydrol. Res.* 53, 14–28.
- Salo, H., Salla, A., Koivusalo, H., 2021. Seasonal effects of controlled drainage on field water balance and groundwater levels. *Hydrol. Res.* 52, 1633–1647.
- Schaap, M.G., Leij, F.J., Van Genuchten, M.T., 2001. Rosetta: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *J. Hydrol.* 251, 163–176.
- Singh, N., Kogan, C., Chaudhary, S., Rajagopalan, K., LaHue, G.T., 2022. Controlled drainage and subirrigation suitability in the United States: A meta-analysis of crop yield and soil moisture effects. *Vadose Zone J.* 21, e20219.
- Sloan, B.P., Basu, N.B., Mantilla, R., 2016. Hydrologic impacts of subsurface drainage at the field scale: Climate, landscape and anthropogenic controls. *Agric. Water Manag.* 165, 1–10.
- Sojka, M., Kozłowski, M., Kęsicka, B., Wróżyński, R., Stasik, R., Napierata, M., Jaskuła, J., Liberacki, D., 2020. The effect of climate change on controlled drainage effectiveness in the context of groundwater dynamics, surface, and drainage outflows. Central-western Poland case study. *Agronomy* 10, 625.
- Stumpp, C., Engelhardt, S., Hofmann, M., Huwe, B., 2009. Evaluation of pedotransfer functions for estimating soil hydraulic properties of prevalent soils in a catchment of the Bavarian Alps. *Eur. J. For. Res.* 128, 609–620.
- Sun, H., Tong, J., Luo, W., Wang, X., Yang, J., 2016. Simplified continuous simulation model for investigating effects of controlled drainage on long-term soil moisture dynamics with a shallow groundwater table. *Environ. Sci. Pollut. Res.* 23, 15565–15573.
- Tebbens, J.A., Stuyt, L.C.P.M., Van Bakel, J., 1999. Hydrologie op basis van karteerbare kenmerken. Alterra.

- Tolomio, M., Borin, M., 2019. Controlled drainage and crop production in a long-term experiment in North-Eastern Italy. *Agric. Water Manag.* 222, 21–29. <https://doi.org/10.1016/j.agwat.2019.05.040>.
- U.S. Department of Agriculture, A.R.S., 2019. ROSETTA Class Average Hydraulic Parameters [WWW Document]. URL <https://www.ars.usda.gov/pacific-west-area/riverside-ca/agricultural-water-efficiency-and-salinity-research-unit/docs/model/rosetta-class-average-hydraulic-parameters/> (accessed 6.8.24).
- Van de Craats, D., Van der Zee, S., Leijnse, A., 2021. Anticipatory drainage base management for groundwater level optimization. *Water Resour. Res.* 57, e2021WR029623.
- Van den Eertwegh, G.A.P.H., Droogers, P., 2013. *KlimaatAdaptieve Drainage: analyse van kosten en baten voor waterbeheerder en agrariër* (Report No. 120), Eindrapportage Werkpakket 5: Economisch onderzoek. FutureWater, Netherlands.
- Vanongeval, F., Gobin, A., 2023. Adverse Weather Impacts on Winter Wheat, Maize and Potato Yield Gaps in northern Belgium. *Agronomy* 13, 1104. <https://doi.org/10.3390/agronomy13041104>.
- Vermeulen, J., Grotenhuis, T., Joziassse, J., Rulkens, W., 2003. Ripening of clayey dredged sediments during temporary upland disposal a bioremediation technique. *J. Soils Sediment.* 3, 49–59.
- Wang, T., Istanbuluoglu, E., Lenters, J., Scott, D., 2009. On the role of groundwater and soil texture in the regional water balance: An investigation of the Nebraska Sand Hills, USA. *Water Resour. Res.* 45.
- Wang, Z., Shao, G., Lu, J., Zhang, K., Gao, Y., Ding, J., 2020. Effects of controlled drainage on crop yield, drainage water quantity and quality: a meta-analysis. *Agric. Water Manag.* 239, 106253. <https://doi.org/10.1016/j.agwat.2020.106253>.
- Xu, X., Huang, G., Zhan, H., Qu, Z., Huang, Q., 2012. Integration of SWAP and MODFLOW-2000 for modeling groundwater dynamics in shallow water table areas. *J. Hydrol.* 412, 170–181.
- Youssef, M.A., Abdelbaki, A.M., Negm, L.M., Skaggs, R.W., Thorp, K.R., Jaynes, D.B., 2018. DRAINMOD-simulated performance of controlled drainage across the US Midwest. *Agric. Water Manag.* 197, 54–66.
- Youssef, M.A., Liu, Y., Chescheir, G.M., Skaggs, R.W., Negm, L.M., 2021. DRAINMOD modeling framework for simulating controlled drainage effect on lateral seepage from artificially drained fields. *Agric. Water Manag.* 254, 106944. <https://doi.org/10.1016/j.agwat.2021.106944>.
- Youssef, M.A., Strock, J., Bagheri, E., Reinhart, B.D., Abendroth, L.J., Chighladze, G., Ghane, E., Shedekar, V., Fausey (Ret.), N.R., Frankenberger, J.R., Helmers, M.J., Jaynes (Ret.), D.B., Kladvko, E., Negm, L., Nelson, K., Pease, L., 2023. Impact of controlled drainage on corn yield under varying precipitation patterns: A synthesis of studies across the U.S. Midwest and Southeast. *Agric. Water Manag.* 275, 107993. <https://doi.org/10.1016/j.agwat.2022.107993>.
- Yu, F., Frankenberger, J., Ackerson, J., Reinhart, B., 2020. Potential suitability of subirrigation for field crops in the US Midwest. *Trans. ASABE* 63, 1559–1570.
- Zipper, S.C., Soyulu, M.E., Booth, E.G., Loheide, S.P., 2015. Untangling the effects of shallow groundwater and soil texture as drivers of subfield-scale yield variability. *Water Resour. Res.* 51, 6338–6358. <https://doi.org/10.1002/2015WR017522>.