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Controlled drainage with subirrigation systems: Reduce water supply by automatic control

J.A. (Janine) de Wit [a,b,*], J.C. (Jos) van Dam [b], G.A.P.H. (Gé) van den Eertwegh [c], M.H.J. (Marjolein) van Huijgevoort [a,d], C.J. (Coen) Ritsema [b], R.P. (Ruud) Bartholomeus [a,b]

[a] KWR Water Research Institute, Nieuwegein, the Netherlands
[b] Soil Physics and Land Management, Wageningen University & Research, Wageningen, the Netherlands
[c] KnowH2O, Berg en Dal, the Netherlands
[d] Institute for Environmental Studies, Vrije Universiteit Amsterdam, Amsterdam, the Netherlands

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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 paper 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 235–628 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.

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 paper 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

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Abbreviations: CAD, climate adaptive drainage; CAD-MA, climate adaptive drainage management algorithm; CD, controlled drainage; CDSI, controlled drainage with subirrigation; CDSI-fix, controlled drainage with subirrigation with a fixed crest height in the control pit; CDSI-dyn0, controlled drainage with subirrigation with a dynamic crest height in the control pit and accepting 0 % oxygen and drought stress; CDSI-dyn10 – CDSI-dyn40, controlled drainage with subirrigation with a dynamic crest height in the control pit and accepting 10 % oxygen and drought stress or 20, 30, 40 %.

* Corresponding author at: KWR Water Research Institute, Nieuwegein, the Netherlands
E-mail address: janine.de.wit@kwrwater.nl (J.A. (Janine) de Wit).

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(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 (Fig. 1). The collector pipe is connected with a control pit and the control pit is connected with an adjacent ditch. The crest level (Hcrest) in the control pit can be set online or manually. The set Hcrest results in a drainage base (WLpit) 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 500–1000 mm) (De Wit et al., 2024; 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 (Wsupply) 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 at 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 (Fig. 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.

2. Methods

2.1. Experimental site

We focus on an experimental site located in the southeast of the Dutch sandy Pleistocene uplands (town America; 51°27'N, 5°57'E) where CDSI was applied (Fig. 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 (Fig. 2-II). The 17 drainage pipes (each approximately 400 m long and the pipes were about level) were placed perpendicular to the collector drain, at roughly 1.20 m below soil surface (m-ss) with 6 m spacing. Two shallow piezometers were

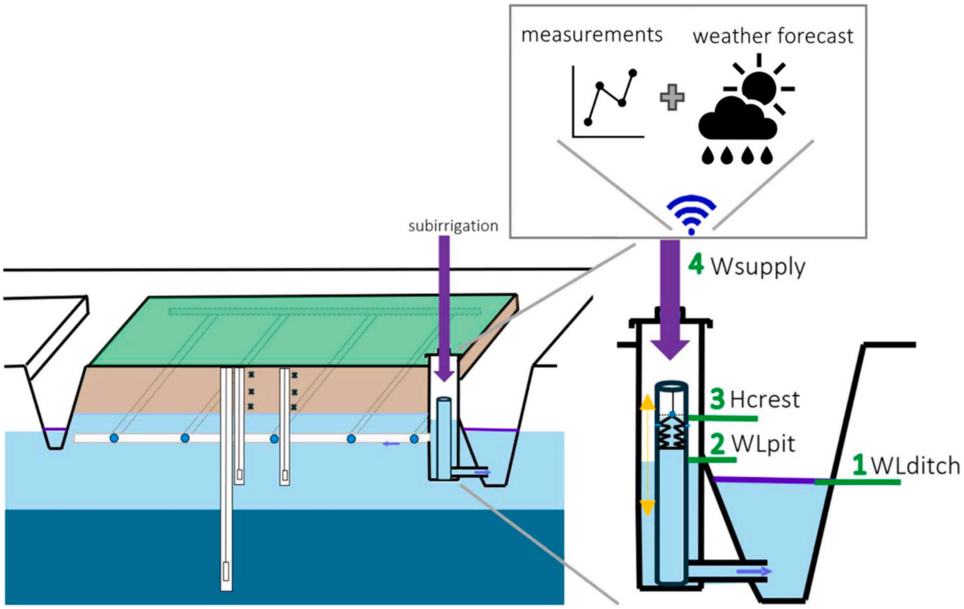

Fig. 1. Schematization of an automatically controlled drainage system with subirrigation. The drainage pipes are represented in grey. The ditch water level (1, 'WLditch'), pit water level or drainage base (2, 'WLpit'), height of the fixed or online controlled weir in the pit (3, 'Hcrest'), and the water supply (4, 'Wsupply') are indicated. Optimal Hcrest 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, WLditch, WLpit, Hcrest and Wsupply. Figure adapted from De Wit et al. (2024).

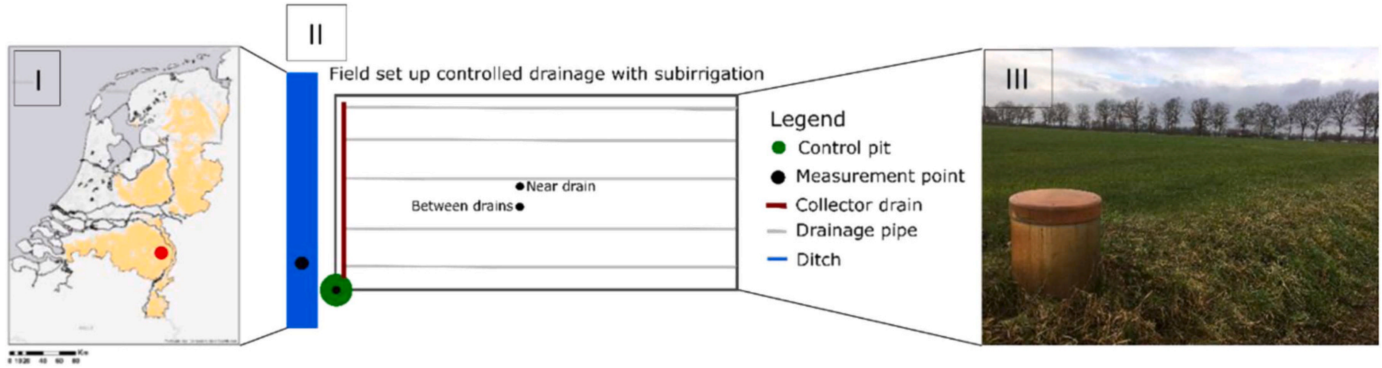

Fig. 2. The Netherlands with the (drought sensitive) sandy Pleistocene uplands in yellow (I) (0 – 100 m+MSL). The red dot represents the location of the field experiment. II: schematic field setup of CDSI. III: a picture of the control pit at the experimental field site.

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 (Fig. 1). The crops were (perennial rye) grass (2017–2019, 2021–2022) and carrots (2020). The phreatic groundwater levels varied between 90 and 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. (2024). The details of the parameters for these soil layers are described in Table 1 and are included in the *.swp file in the supplementary material. The field surface area is 3.77 ha with an average field height of 30.72 m above mean sea level (m+MSL). A reference field with similar equipment but no subirrigation was located adjacent to the subirrigation field.

The field measurements are schematized in Fig. 1. Wsupply was measured daily with the ZENNER PN16 - Qn 6 BH (2017–2020) and a KAMSTRUP flowIQ® 3100 m (2021–2022). WLpit was measured every 15 minutes with the KELLER DCX-22. WLpit, the groundwater level (GWL) and the hydraulic head were measured every 15 minutes with a CTD-10 sensor (METER). Hcrest was in practice almost always at 50 cm-ss. Soil moisture content (SMC) and soil water pressure head (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. (2023).

Table 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. (2024).

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

2.2. Field scale modelling

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. (2024). The ‘first order drainage system’ is used to simulate ditch drainage and infiltration for which ditch water levels (WLditch, Fig. 1) are input. The ‘secondary drainage system’ is used to simulate controlled drainage with subirrigation.

2.2.2. SWAP modelling for four drainage systems

One general SWAP model was set up in this study based on the schematization of Fig. 1 and the field site A described in De Wit et al. (2024). 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., 2024)). The ditch drainage resistance determines the drainage to the ditch (defined as lateral drainage) and was calibrated on

350 d (De Wit et al., 2024). Ditch level was 150 cm-ss. Input files *.swp, *.dra and GrassS.crp are provided as Supplementary Material. Output (per day) is, among other things, the actual water supply for subirrigation, WLpit, groundwater level, 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 (Fig. 3): i) Conventional drainage aims to discharge water; yearly Hcrest = 120 cm-ss (equal to drain depth), ii) Controlled drainage aims to both retain and discharge water; Hcrest = 50 cm-ss (year-round), based on field experiments (De Wit et al., 2024), iii) CDSI-fixed aims to retain, recharge, and discharge water. Hcrest 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., 2024). 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., 2024), 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 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.

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 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.

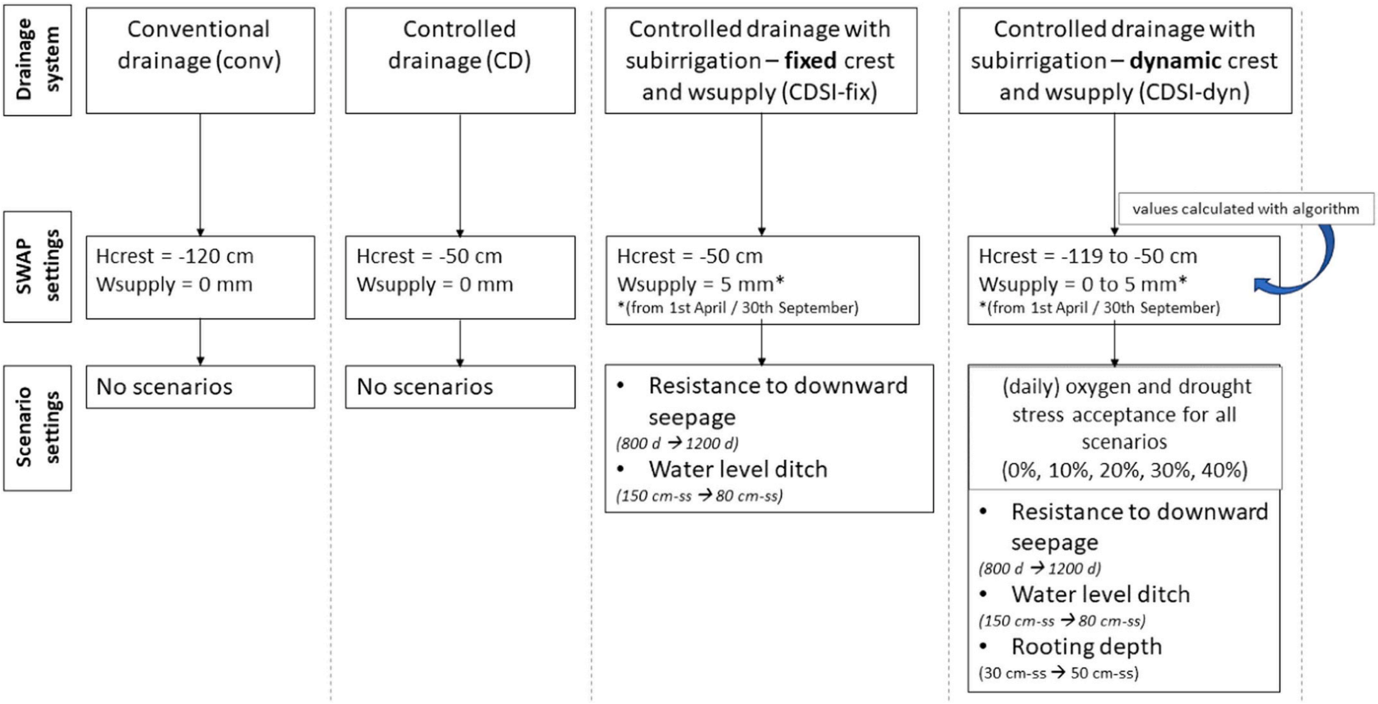

Fig. 3. Overview of all simulations with the field scale model SWAP. In total, four drainage systems (conventional drainage, controlled drainage, CDSI fixed and CDSI dynamic) were simulated for 10 years (2013–2022). CDSI (fixed and dynamic) were simulated with subtle differences in geohydrological characteristics (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.

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).

2.2.4. *CDSI scenarios*

CDSI (fixed and dynamic) systems were also simulated with subtle differences in geohydrological characteristics and crop rooting depth (Fig. 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 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 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.

3. Results

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 (Fig. 3, Fig. 4C), and a corresponding pit water level of approximately 120 cm-ss (Fig. 4D). A low pit level resulted in a groundwater level fluctuating between 100 cm-ss and 250 cm-ss (Fig. 4E) with the consequence of high cumulative yearly drought stress, especially in the drier years 2018, 2020, 2022 (Fig. 4G), and yearly cumulative oxygen stress between 0 and 4 mm (i.e. negligible) (Fig. 4H). Lateral ditch drainage was maximal 1 mm/d because the groundwater level was generally lower than the surface water level (Fig. 4I). Therefore, water mainly exited the system as downward seepage ranging from 0 to 1.5 mm/d (Fig. 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 (Fig. 4D). A higher pit level also resulted in a slight increase in groundwater level in wintertime compared to conventional drainage (Fig. 4E). The retention of water slightly reduced drought stress in the dry year 2020 (200 mm/y) compared to conventional drainage (220 mm/y) (Fig. 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) (Fig. 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 (Fig. 4B) and a fixed crest level of 50 cm-ss (Fig. 4C). A high crest level resulted in a fluctuating pit water level between 50 cm-ss and 120 cm-ss (Fig. 4D). As a result, the groundwater level ranged between 30 cm-ss and 120 cm-ss (Fig. 4E) and drought stress ranged between 0 and 50 mm/y (Fig. 4G). Oxygen stress was negligible (up to 1 mm/y) (Fig. 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 (Fig. 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 (Fig. 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 (Fig. 4G), including acceptance of 10 % daily drought stress. Oxygen stress was up to 0.5 mm/y (Fig. 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.

Drainage systems affected the main water balance components (Fig. 5). Fig. 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.

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 (Fig. 4). First, for CDSI-fix, Wsupply 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

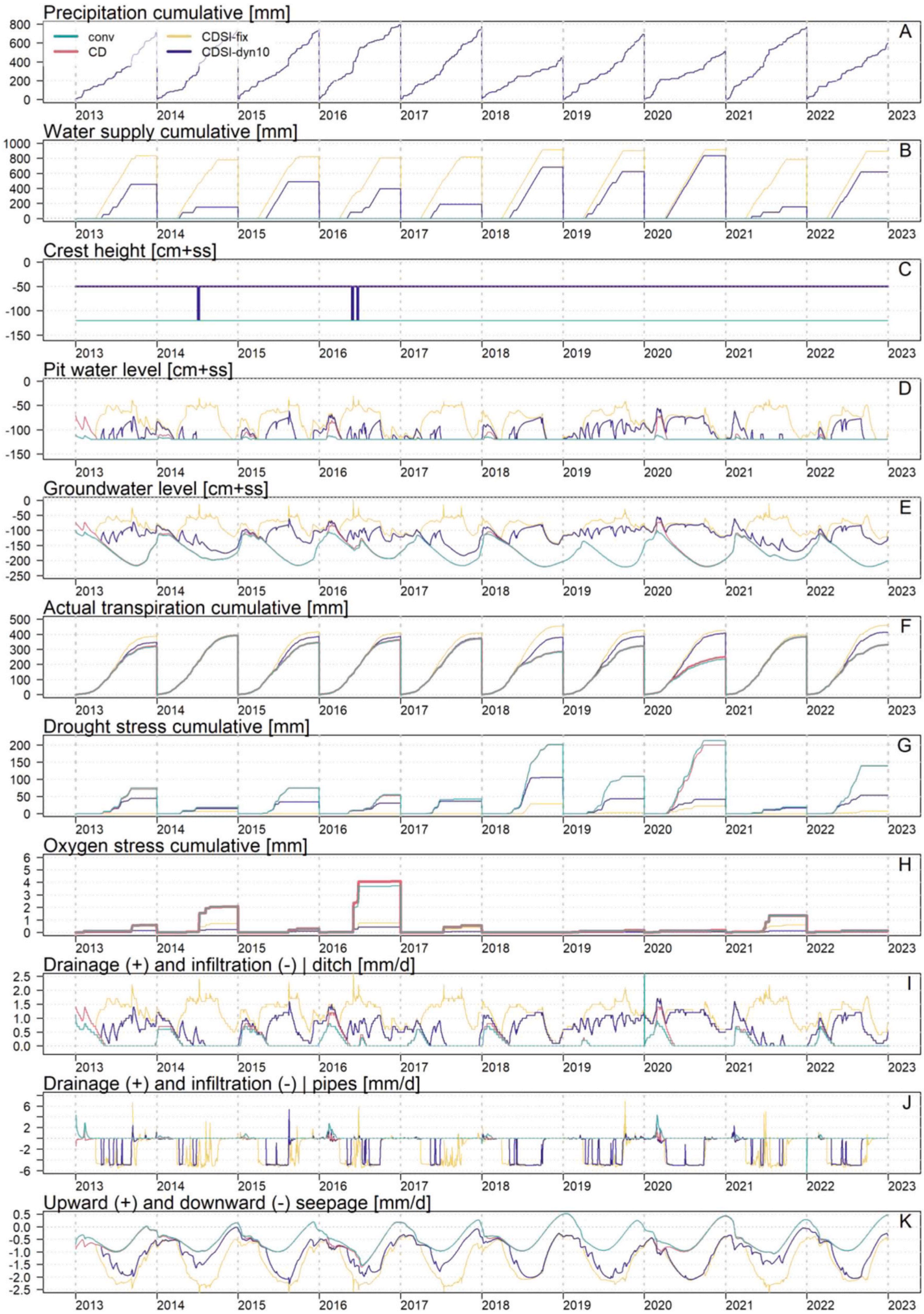

Fig. 4. Overview of measured cumulative precipitation of the KNMI station Arcen (A), cumulative water supply (B), crest height (C), pit water level (D), groundwater level (E), cumulative actual transpiration (F), cumulative drought stress (G), cumulative oxygen stress (H, please note the difference in 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 Hcrest 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 %’).

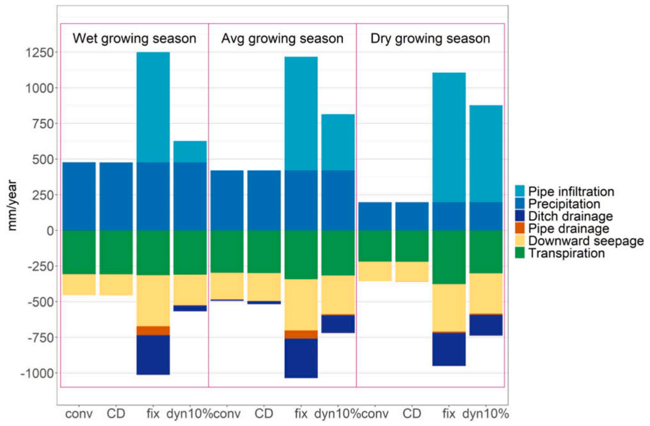

Fig. 5. Simulated water balance components over the growing season (1st April – 30th September). All components are calculated for a relative wet growing season (2014, 'wet growing season'), an average growing season (2016, 'avg growing season') and an extremely dry growing season (2018, 'dry growing 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 %').

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.

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 (Fig. 6). CDSI-fix systems required an almost similar water supply in drier and wetter years (roughly 900 vs 800 mm/y respectively) (Fig. 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 Wsupply 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) (Fig. 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 Wsupply 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 (Fig. 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 (Fig. 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.

3.3. *Impact of geohydrological and crop characteristics*

3.3.1. *Changes in water supply of CDSI systems*

Geohydrological characteristics impacted the water demand of CDSI systems (Fig. 6A). Effects were different for a fixed or a dynamic CDSI system. For CDSI-fix this meant (Fig. 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 (Fig. 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/

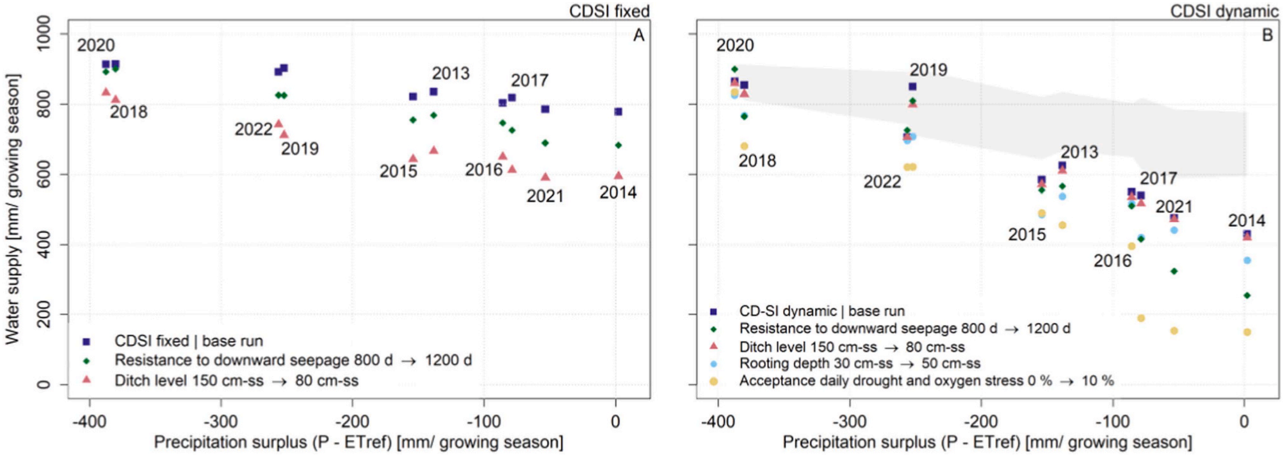

Fig. 6. The calculated precipitation surplus (P – ET_{ref}) in the growing season (1st April – 30th September) versus water supply in the growing season for controlled drainage with subirrigation (CDSI) system using a fixed crest and water supply (A) and using a dynamic crest and water supply (B). Fixed 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.

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.

Changes in ditch level, hydraulic resistance to downward seepage, and changes in rooting depth affected ditch and pipe drainage fluxes, downward seepage and transpiration (Fig. 7). Fig. 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 A, Figure A1). 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) (Fig. 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) (Fig. 7).

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)) (Fig. 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.

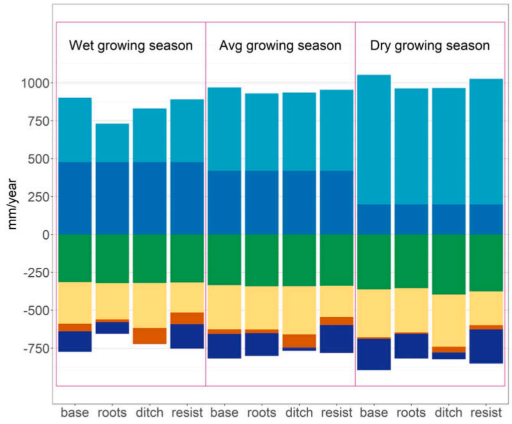

Fig. 7. Simulated water balance components with the SWAP model, via the algorithm with a dynamic crest level and dynamic water supply. All components were calculated over the growing season (1st April – 30th September) for a relative wet growing season (2014, 'wet growing season'), an average growing 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').

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) (Fig. 8A). Acceptance of daily oxygen and drought stress (10–40 %) 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 (Fig. 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) (Fig. 8A).

Overall, it seems that 200 mm water supply acts as a threshold: if 0–200 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 (Fig. 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.

Geohydrological and root characteristics impacted the water supply and thus yield reduction (Fig. 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 Hcrest 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

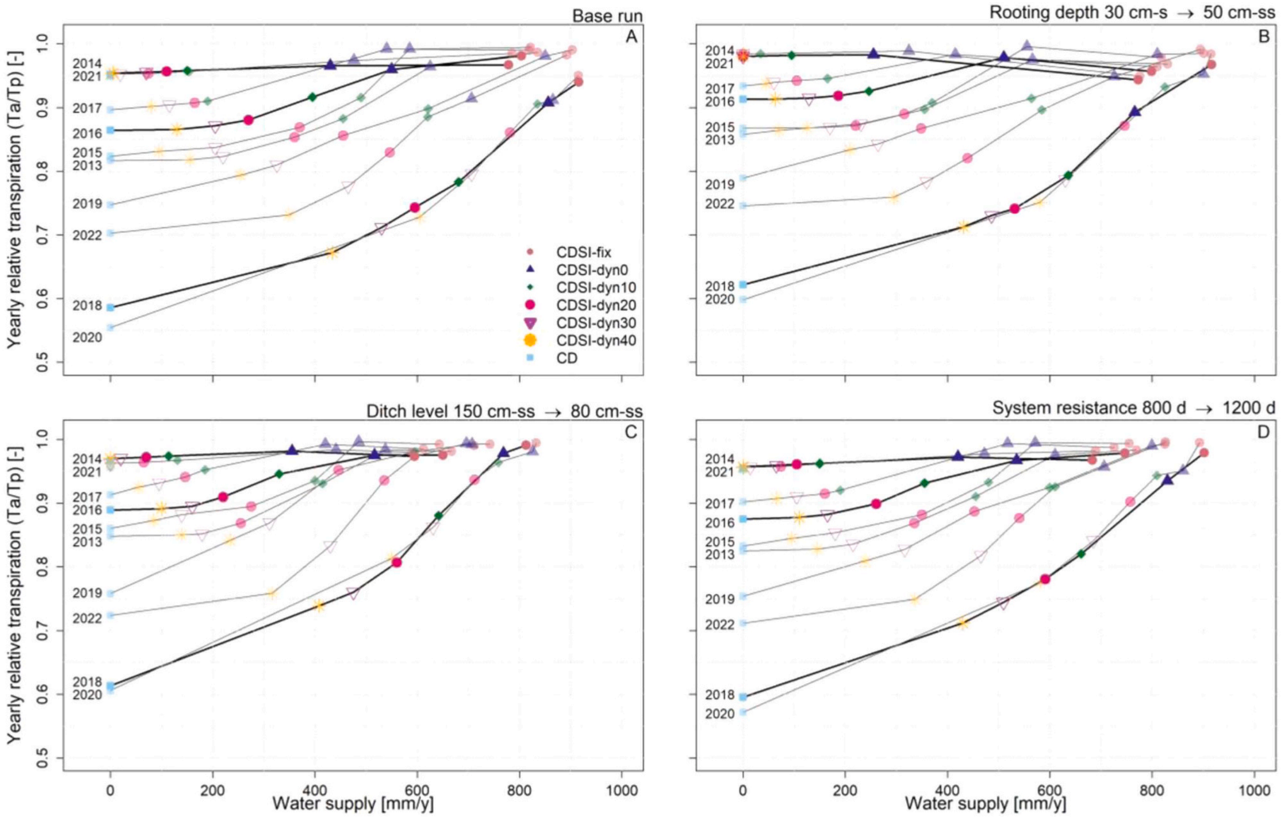

Fig. 8. Yearly relative transpiration (actual transpiration divided by potential transpiration) and yearly water supply calculated with the SWAP model for 10 years (2013 – 2022) for controlled drainage with subirrigation (CDSI) using a fixed crest level of −50 cm and daily 5 mm water supply in the growing 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).

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.

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. Fig. 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, Fig. 9 shows the changes in hydrological fluxes as result of deeper roots or a higher ditch level for the respective drainage systems.

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 (Fig. 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 (Fig. 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, Fig. 9 shows a maximum (upper threshold) for transpiration

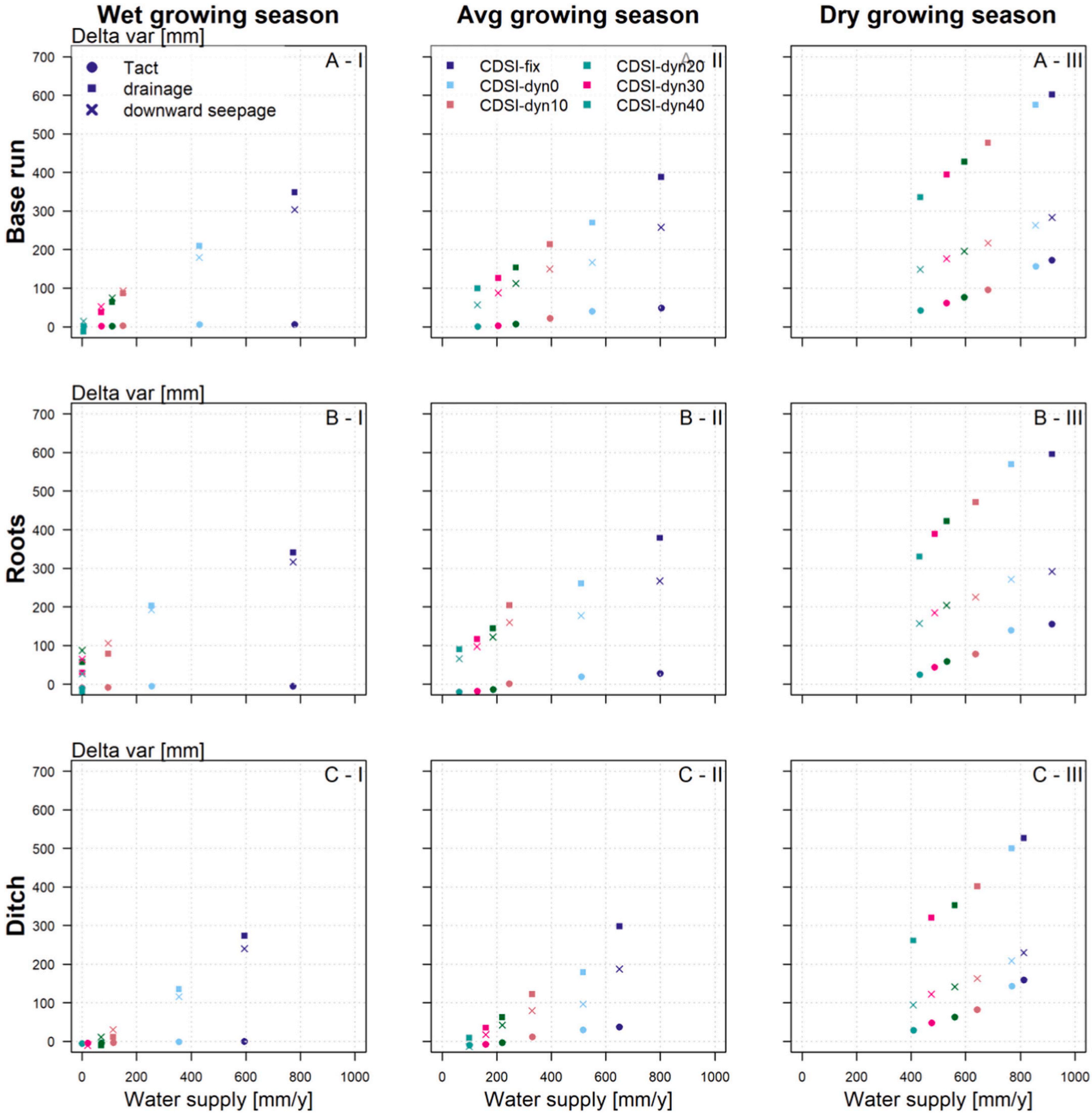

Fig. 9. Change (‘Delta’) of actual transpiration (‘Tact’), total drainage (pipe drainage + lateral drainage, ‘drainage’) and downward seepage as function of water supply. Delta is defined as the difference between controlled drainage of the base run minus a variation of a drainage system (‘CDSI-fix’, ‘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.

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. 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 (Fig. 4). Conversely, the crest level must be kept high, so that water is retained in winter for the next summer, like in 2019 (Fig. 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 (Fig. 8).

The differences in water demand varied in this study between 0 and 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., 2024). 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 paper. Furthermore, although the results in this paper were based on a modelling study, De Wit et al. (2024) 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 scenario's, 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 weather years. Field experiments usually span a limited number of weather 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 crest level 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 Hcrest 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 paper. However, the increased transpiration corresponds to the results in this paper.

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 12–21 % 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 B, Figure B1).

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.

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.

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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.

Data availability

Data will be made available on request.

Acknowledgements

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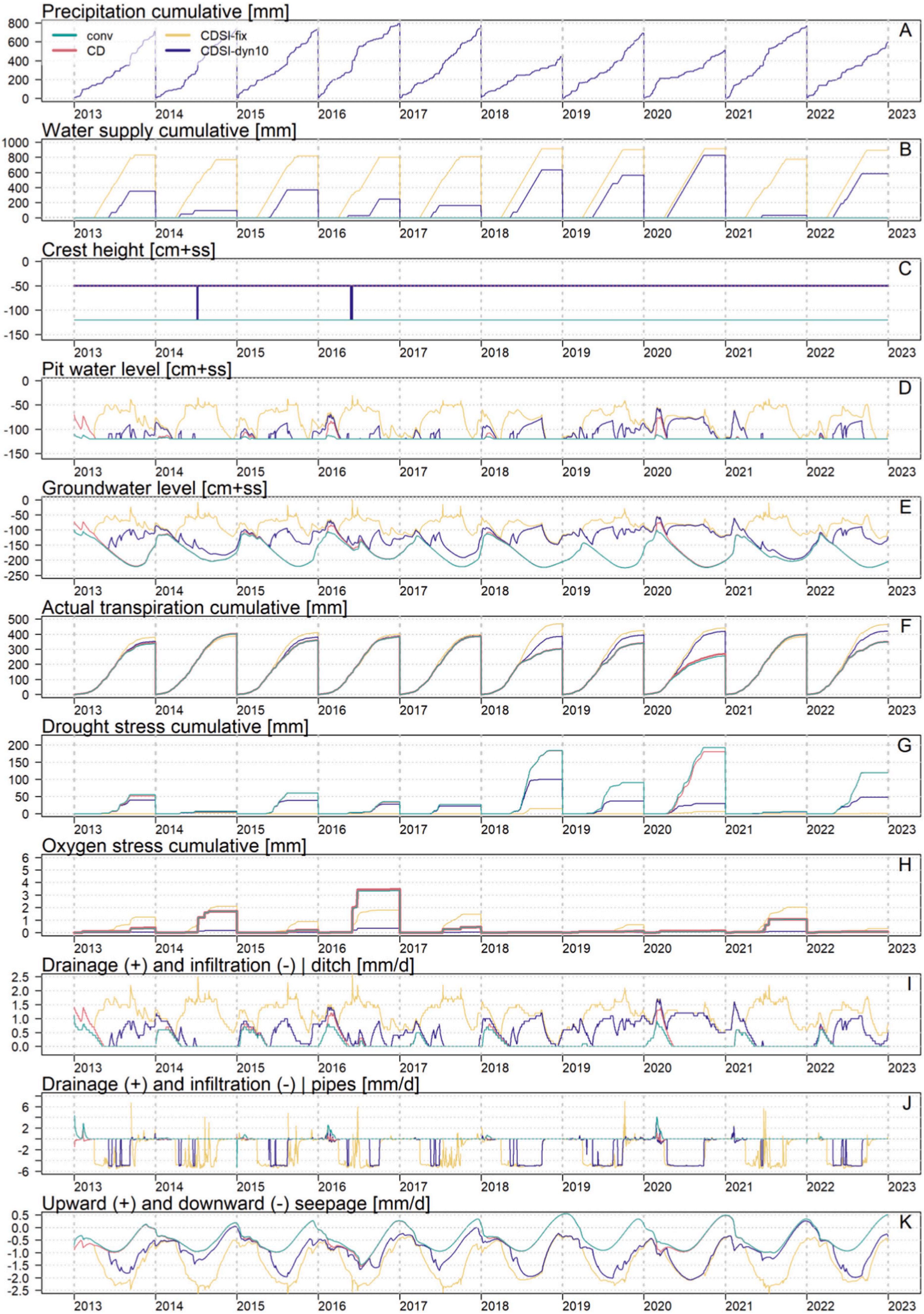
Appendix A. Hydrological consequences for simulations with larger rooting depth


Precipitation cumulative [mm]

Water supply cumulative [mm]

Crest height [cm+ss]

Pit water level [cm+ss]

Groundwater level [cm+ss]

Actual transpiration cumulative [mm]

Drought stress cumulative [mm]

Oxygen stress cumulative [mm]

Drainage (+) and infiltration (-) | ditch [mm/d]

Drainage (+) and infiltration (-) | pipes [mm/d]

Upward (+) and downward (-) seepage [mm/d]

Figure A1. 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 Hcrest 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.

Appendix B. 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 2.2.3) and the daily weather forecast. To do so, three steps were added to the algorithm (Figure B1).

- 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 Hcrest and water 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., 2024).

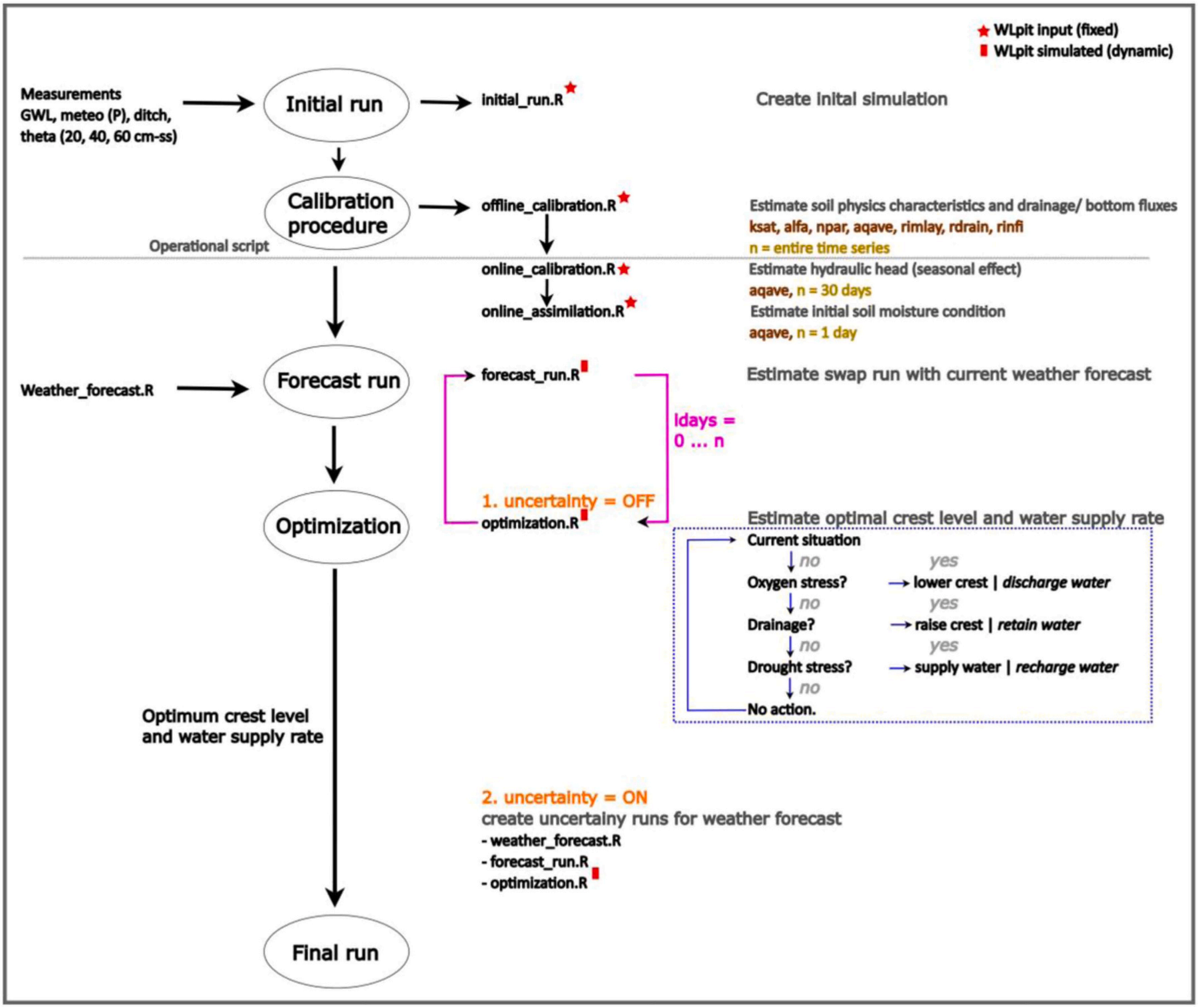


Figure B1. CAD-algorithm consisting of five steps; 1) initial SWAP run, 2) calibration procedure in which SWAP is calibrated with PEST based on field measurements, 3) forecast run including the weather forecast, 4) optimization run, and 5) the final SWAP run. The SWAP simulations differ between fixed pit levels (indicated with a red star) and a dynamic pit level (indicated with a red rectangle).

Appendix C. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2024.109022.

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