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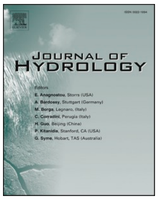

Research papers

Hydrological consequences of controlled drainage with subirrigation

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ABSTRACT

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

1. Introduction

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

Drainage systems have been widely installed to remove water in wet periods. About 34 % of the Dutch agricultural land, for example, contains pipe drainage (Massop and Schuiling, 2016). Later, some of these systems were converted to controlled drainage to also retain water by

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Abbreviations: CAD, climate adaptive drainage; CD-SI, controlled drainage with subirrigation; CV, coefficient of variation; Hcrest, height of the fixed or online controlled weir in the pit; GWL, groundwater level; KNMI, Royal Netherlands Meteorological Institute; KGE, Kling-Gupta efficiency; MHG, mean highest groundwater level; MLG, mean lowest groundwater level; RMSE, root mean square error; RSR, error index statistics root mean square error-observations standard deviation ratio; SWAP, Soil Water Atmosphere and Plant model; SMC, soil moisture content; SWP, soil water potential; WLditch, ditch water level; WLpit, water level in the control pit; Wsupply, water supply; WWTP, wastewater treatment plant.

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reducing drainage (Ayars et al., 2006; Skaggs et al., 2012a). Nowadays, these controlled drainage systems can also be used to pump water into the system and recharge groundwater, called 'subirrigation' (hereafter controlled drainage with subirrigation CD-SI) (De Wit et al., 2022; Singh et al., 2022). An external water source of a sufficient water quality has to be available for subirrigation. Different CD-SI applications have been described (e.g. Ayars et al. (2006), Bartholomeus et al. (2018), Hay et al. (2021), Narain-Ford et al. (2021)). CD-SI systems can be controlled manually or online (climate adaptive drainage (CAD), van den Eertwegh et al. (2013)). A key component in the functioning of CD-SI systems is the created water level in the control pit as it either forms the drainage base ('discharge', 'retention') or provides the pressure for infiltration ('recharge') (Evans and Skaggs, 1985; Tang, 2022).

The implementation of CD-SI systems could alter several water balance components (Fig. 1). The groundwater level could raise (Drury et al., 1996), and depending on both soil physical conditions determining capillary rise, and crop rooting depth, it could increase crop water availability and crop yield (Ng et al., 2002). However, not all water balance components can be measured. Models as DRAINMOD (Skaggs et al., 2012b), Hydrus (Šejna et al., 2022) and SUTRA (Voss and Provost, 2010) have been applied to design and model CD-SI systems. Although models implementing CD-SI systems have been described in literature over the past decades, the water level in the control pit (fixed head) or water supply rate (fixed flow) have been considered constants. However, they depend on the drainage threshold in the pit, groundwater level, maximum available external water supply, drainage resistance and infiltration resistance. Therefore, dynamic modelling is required for correct insights in the water balance components and effective implementation of subirrigation (Doty et al., 1986; Evans, 2008). This results in the following research question to be addressed in this study: What are the hydrological consequences of subirrigation and how can these consequences be simulated using a field scale agro-hydrological model?

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

2. Methods

2.1. Experimental sites

2.1.1. Characteristics field sites

CD-SI was applied at four locations in the Dutch sandy Pleistocene uplands (Fig. 2-I, II). The general set up of each drainage system is a control pit connected with a collector drain parallel to a ditch (Fig. 2-III). The drainage pipes are placed perpendicular to the collector drain, at roughly 1.20 m-soil surface (ss) with 6–10 m spacing. At each site two piezometers are installed near and between two drains (Fig. 2-III). The measurements are explained in detail in Fig. 3 and described in section 2.1.2. Some specific geohydrological field characteristics are:

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

The main geohydrological characteristics of all sites are explained in Table 1. Site A is used to describe the applied methods in detail. All sites are modelled in the same way to quantify the effect of CD-SI systems on components of the water balance for different geohydrological characteristics.

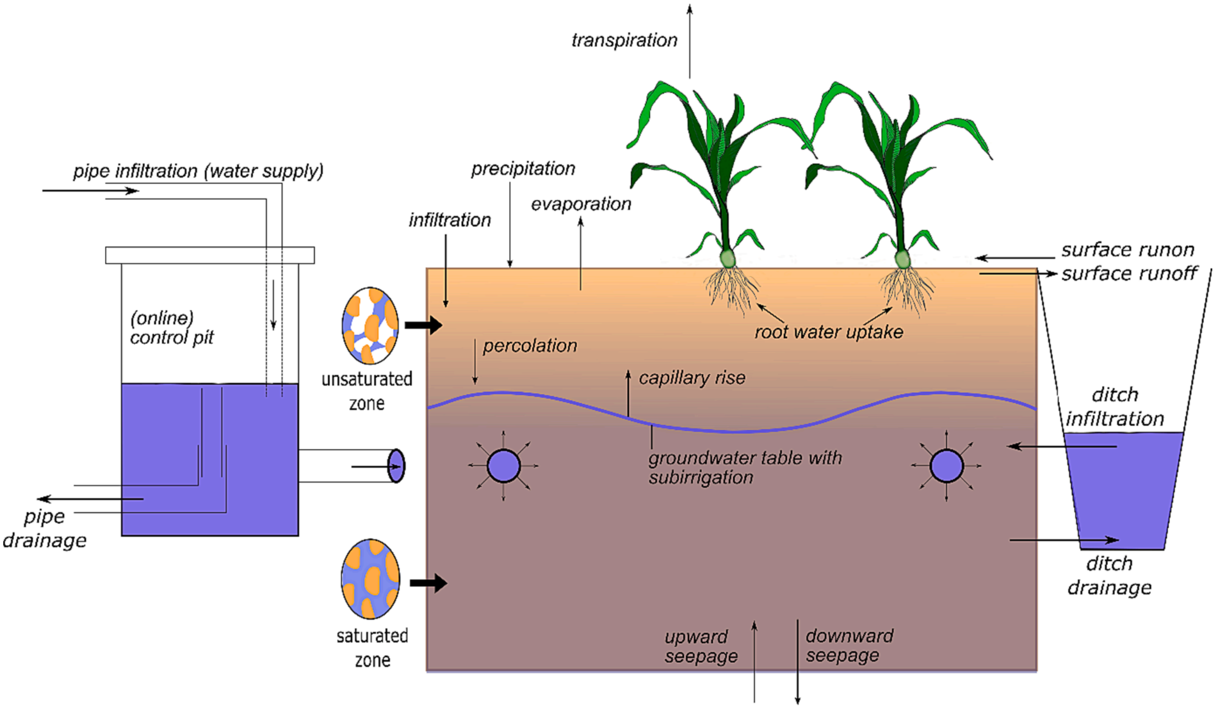

Fig. 1. The soil water column at field scale with the water balance components in the (un)saturated zone (De Wit et al., 2022).

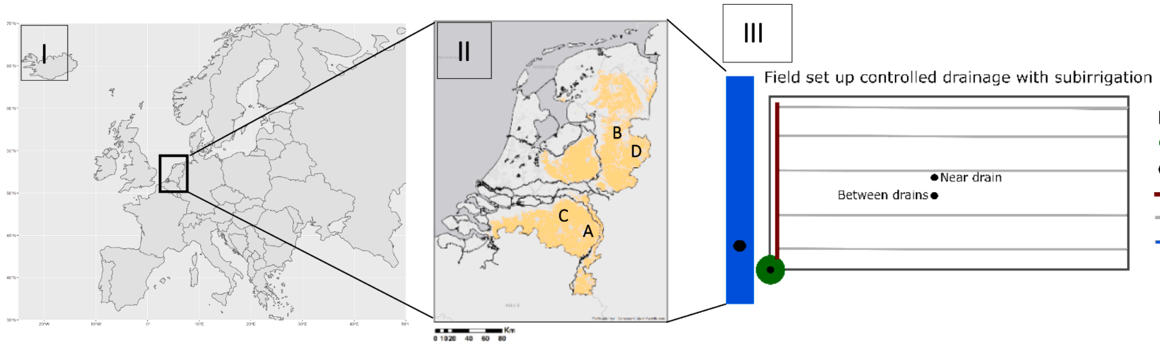

Fig. 2. The Netherlands (I) with the (drought sensitive) sandy Pleistocene uplands (II, yellow) (0 – 100 m + MSL). The letters A, B, C and D represent the locations of the field experiments. III: Schematic field setup.

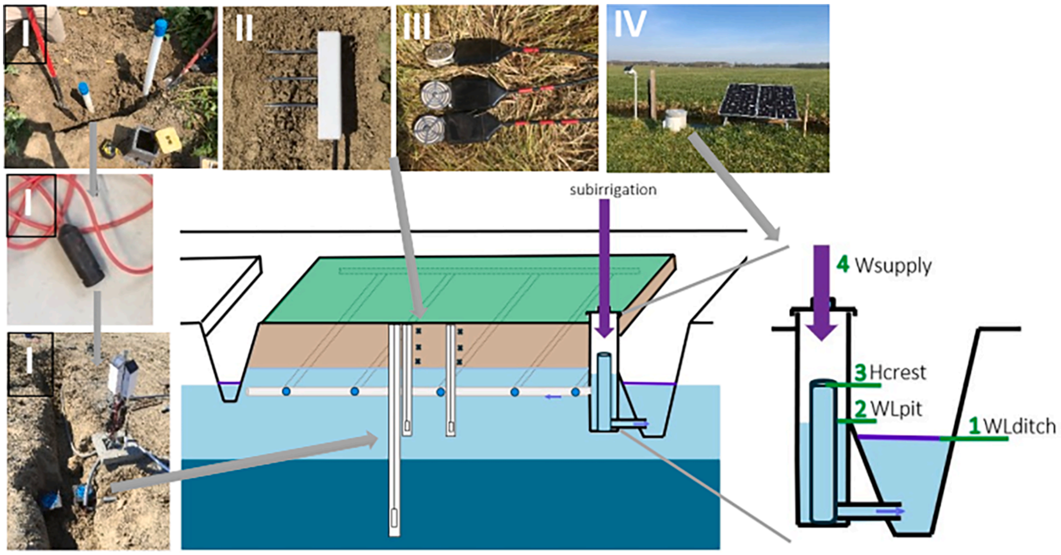

Fig. 3. Schematization of a subirrigation system with the installed measurement devices. The drainage pipes are represented with dotted lines. Measurements are: shallow and deep hydraulic head (I), soil moisture content at 20, 40 and 60 cm depth (II), the soil water potential at 20, 40, 60 cm depth (III),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

Table 1
(Geohydrological) characteristics of the four experimental field sites with CD-SI systems (Fig. 2). The average field height is also used as average soil surface in the field scale modelling.

		Site A	Site B	Site C	Site D
Source water supply		Groundwater	Surface water	Industrial effluent	WWTP effluent*
Location (town, coordinates)		America, 51°27′N, 5°57′E	Stegeren, 52°54′N, 6°51′E	Lieshout, 51°52′N, 5°62′E	Haaksbergen, 52°18′N, 6°71′E
Field area [ha]		3.77	2.5	8.5	5.85
Average field height [m + mean sea level (MSL)]		30.94	7.35	16.55	20.76
MxG	MHG* [cm-ss]	~ 90	~ 80	~ 100	~ 25
	MLG* [cm-ss]	~ 180	~ 120	~ 230	~ 100
Ditch level	Winter [cm-ss]	160	120	380	170
	Summer [cm-ss]	150	85	350	170
Crop		Grass (2017–2019) Carrot (2020) Grass (2021 – 2022)	Grass (2018–2022)	Grass (2015–2020)	Maize (2016–2020) Grass (2021–2022)
Soil		Sand, loam > 2–2.5 m-ss	Sand, loam - none	Sand, Loamy layers > 1–1.5 m-ss	Sand, Loamy layers > 3 m-ss
Time period		2017–2022	2018–2022	2015–2020	2016–2020
Includes reference field		Yes	Yes	No	No
Nearby KNMI station nr.		391	278	370	290

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

2.1.2. Set up measurements at the field sites

A schematic overview of a CD-SI system including the drainage pipes, control pit, weir mechanism and ditch is given in Fig. 3. The weir mechanism could be controlled online (site B and D) or manually (site A and C). All four field sites were equipped with measurement devices for: precipitation (duration and amount), water supply (flow), shallow and deep hydraulic head, soil moisture content (SMC) (and soil water potential (SWP) at site A) at 20, 40, and 60 cm depth, water level in the CD-SI control pit and the ditch water level (Fig. 3). At sites A and B also a reference field without drainage was equipped with measurement devices for: shallow and deep hydraulic head and SMC (and SWP at site A) at 20, 40, and 60 cm depth. The sensors in the reference field of site A and the SWP sensors at the subirrigation field of site A were installed in June 2021. Meteorological measurements were used from nearby weather stations from the Royal Netherlands Meteorological Institute (KNMI) (Table 1).

2.2. Field scale modelling

2.2.1. Field scale model SWAP

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

SWAP contains different boundary conditions to simulate the soil water movement, as also schematically depicted in Fig. 1. The upper boundary condition is given by the atmospheric precipitation and potential evapotranspiration. The simple crop module is a static crop represented as a green canopy that intercepts precipitation, transpires water vapor and shades the ground (Kroes et al., 2017). Main input variables are crop height, rooting depth, soil cover fraction, root length density at different depths in the root zone and crop sensitivity to drought and oxygen stress (Feddes, 1982). In the soil column, the soil hydraulic functions (soil moisture characteristic and hydraulic conductivity function) govern infiltration and soil evaporation at the top and soil moisture redistribution in and below the root zone. The lower boundary condition is represented as bottom flux (upward and downward seepage in Fig. 1) calculated from the hydraulic head in the underlaying aquifer, the resistance to downward flow and the hydraulic head in the shallow aquifer. The hydraulic head in the underlaying aquifer is specified as sine function and is calibrated in this study (section 2.2.3). The side boundaries determine lateral drainage. The lateral drainage flux is incorporated in the numerical solution to the Richards equation as sink term (Kroes et al., 2017). Lateral drainage (i.e. the groundwater- surface water system) is included as a hierarchical system of different drainage levels. Drainage can be modelled via i) the basic drainage option when surface water levels are fixed and ii) via the extended drainage option to calculate dynamic water levels. The 'first order drainage system' is used to simulate ditch drainage and infiltration (Fig. 1), for which ditch water levels (WLditch, Fig. 3) are input and for which the drainage resistance is calibrated (section 2.2.3). The 'secondary drainage system' is used to simulate CD-SI with subirrigation, as further described in section 2.2.2. More details are given in Kroes et al. (2017). Input files *.swp, *.dra and grassS.crp (including soil hydraulic functions, schematization of the lateral drainage, crop characteristics and root water uptake) for SWAP-simulations used in this study are included in the Supplementary Material.

2.2.2. Controlled drainage with subirrigation in field scale model SWAP

CD-SI systems can be modelled in SWAP via either the basic or the extended drainage module. Basic drainage is used when the water level in the pit (WLpit, Fig. 3) is fixed or given as input from measurements. As already mentioned, WLpit is determined by the interplay between the height of the fixed or online controlled weir in the pit (Hcrest, Fig. 3), water supply (Wsupply, Fig. 3) and fluxes in the soil-groundwater-plant-atmosphere system. A fixed or constant WLpit can only be reached when incoming fluxes exceed the total of the outgoing fluxes. In practice, however, the assumption of a constant WLpit does not hold, as Wsupply might be limited. This results in a dynamic WLpit. The extended drainage option in SWAP allows for the dynamic simulation of WLpit, using the controlled drainage system as the 'secondary drainage system' of the extended drainage module. For all simulations, the extended drainage option is used, either with WLpit as input (calibration) or dynamic simulation of WLpit (validation and application) (Fig. 4).

2.2.3. Calibration SWAP model with PEST

For each experimental site, SWAP (version 4.0.1) is calibrated using PEST (Doherty, 2010) to fit the input parameters with the local conditions of the field site (Table 1, Fig. 4). The calibration methodology is described in detail as offline calibration in Bartholomeus et al. (2015b) using the method of Visser et al. (2006). In this approach, soil physical characteristics and system characteristics determining vertical and lateral drainage fluxes are optimized between a realistic range of values (based on literature), such that the (multiple year) time series of measured groundwater levels and soil moisture contents are approached. Possible changes in time of soil physical characteristics and drainage resistances are not considered.

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

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

The calibration is evaluated on the goodness of simulated values compared to observed values of GWL and SMC using root mean square error (RMSE), RMSE-observations standard deviation ratio (RSR), and the Kling-Gupta efficiency (KGE). The goodness of calibrated parameters is evaluated with the dimensionless index for the range of confidence intervals called coefficient of variation (CV) (Doherty, 2004). The RSR includes a normalization factor, so that the index can be applied to

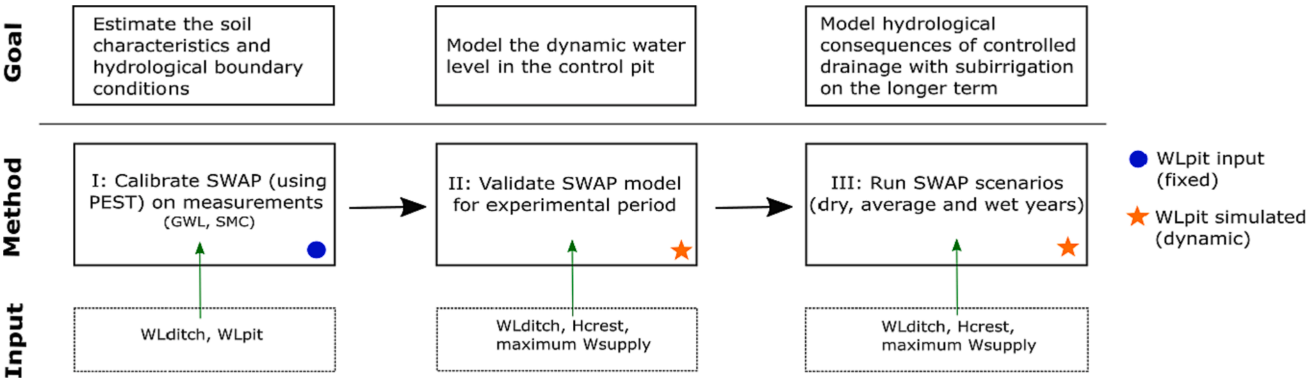

Fig. 4. The goals of SWAP-modelling with the corresponding methods, and used boundary conditions to model the hydrological consequences of controlled drainage with subirrigation based on field measurements.

various constituents (Moriasi et al., 2007). However, RSR gives more weight to high values when compared with low values (Moriasi et al., 2015). The RSR varies between the optimal value 0 to a large positive value (Moriasi et al., 2007). The commonly used and easy to interpret statistic RMSE has an optimal value of 0 (Moriasi et al., 2007). Finally, the KGE expresses the similarity between observed and simulated values (Gupta et al., 2009). Positive KGE values (with a maximum of 1) express good model performance, negative KGE values express bad model performances (Knoben et al., 2019).

2.2.4. *Validation field model SWAP with dynamic simulation WLpit*

Validation of the calibrated model with dynamic simulation of WLpit is performed for the field measurements of all field sites. Input are WLditch, Wsupply and Hcrest. Input files *.swp, *.dra and GrassS.crp for field sites A, B, C, and D are provided as Supplementary Material. The validation step aims to verify if the model is able to simulate the field conditions with the extra complexity of a dynamic simulation of WLpit (needed as explained in Section 2.2.2). The simulated WLpit is compared to the WLpit measurement using RSR, RMSE and KGE (explained in Section 2.2.3).

2.2.5. *Apply field model SWAP for scenario analysis*

The validated SWAP model is used to extend the simulations to the longer period 1993 – 2021, based on the available meteorological conditions. All models have similar input, except for the calibrated parameters and hydrological boundary characteristics, which are based on local conditions of each field (Table 1). This way, the effect of differences in geohydrological characteristics on the functioning and hydrological consequences of CD-SI can be identified.

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

3. Results

In sections 3.1 and 3.2 we focus on measurements and modelling of field site A in detail, and we discuss field sites B, C and D more generally to demonstrate differences for the application of CD-SI systems for different geohydrological conditions. All results of the other sites are included in Appendices.

3.1. *Field measurements*

3.1.1. *Precipitation and water supply*

Precipitation ranges from 445 mm in 2018 to 768 mm in 2021 for site A (Fig. 5A). The long term average yearly precipitation (1993 – 2021) for site A is roughly 733 mm. The precipitation deficit varies from circa 128 mm in July 2018 to −20 mm in June 2021 for site A. The long term average monthly precipitation deficit (1993–2021) for site A varies from + 25 mm in July to + 35 mm in June. The measurement period of 2018 can thus be considered as a very dry year, while 2021 is relatively wet.

Water supply for subirrigation occurs in the growing season from roughly April to October (Fig. 5A). Total water supply at site A ranges from about 1000 mm in 2017 (first year of field experiment) to approximately 200 mm in 2020. This means an average water supply of 4 mmd^{-1} in 2017 and 2018. The water supply between 2019 – July 2021 differs as explained in Appendices. Yearly water supply at field sites B, C, and D ranges from roughly 400 mm to 550 mm. Precipitation at all other sites is comparable to site A.

3.1.2. *Groundwater level and soil conditions*

The shallow groundwater level at the subirrigation field and the deep hydraulic head were similar in winter 2017 (Fig. 5B). Furthermore, the reference shallow groundwater level, shallow groundwater level between drains and deep hydraulic head were similar in spring 2021, when water supply was almost zero. Therefore, the deep hydraulic head was interpreted as the reference situation for the years 2017–2020. The increased difference between the shallow groundwater level and the deep hydraulic head is the result of subirrigation.

The start of the water supply season is clearly visible in the measurements. The shallow groundwater level raises directly as water supply starts (Fig. 5B). Water supply causes a rise of roughly 100 cm in 2021 (relatively wet year) to 150 cm in 2018 (relatively dry year). Similar results are found for site C. The groundwater level at field site B raises with around 30 cm. Because of groundwater level rise, the SMC in the root zone increases via capillary rise. SMC at 60 cm-ss increases at the start of the water supply period in 2017 and 2018 (Fig. 5C). This capillary rise effect is less at 40 cm-ss and smallest at 20 cm-ss (Fig. 5C). SMC at all three depths at field sites C and D increases as a result of subirrigation. At field site B this effect is less pronounced. The SWP at 20 cm-ss at the subirrigation field A varies between −250 hPa to 0 hPa vs −600 hPa to 0 hPa at the reference field. Thereby, the soil at both fields becomes wetter with depth, where the subirrigation field is wetter than the reference field. It indicates drier circumstances at the reference field at site A than at the subirrigation field from August 2021 onwards. SWP at 20 cm-ss increases mid-September 2021 at both the reference field and the CD-SI system field because of sprinkler irrigation.

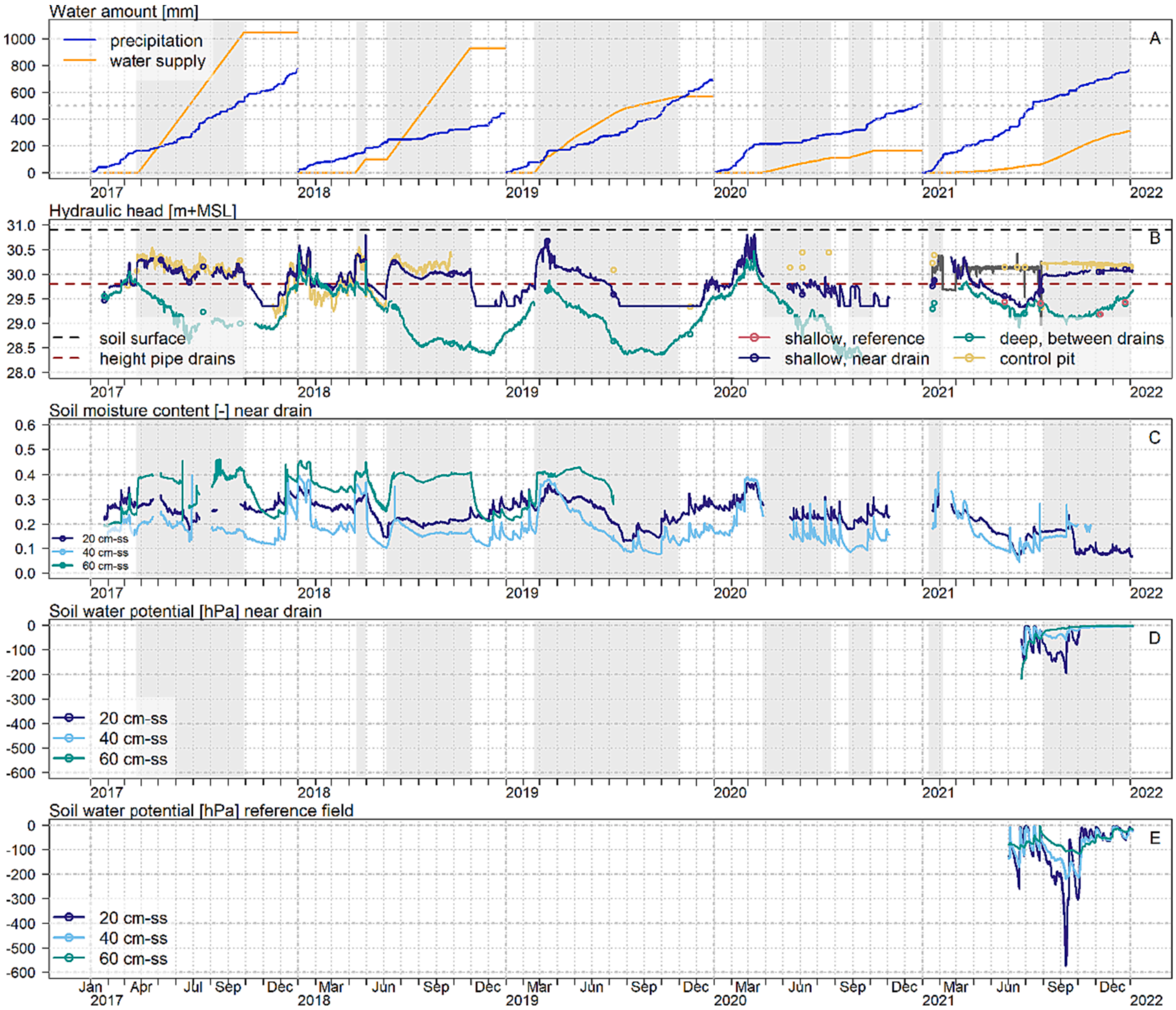

Fig. 5. For site A holds: Precipitation from the automatic KNMI station Arcen and the water supply (A). Shallow groundwater level at the reference field and near the drain, deep groundwater head and water level in the control pit (B). The water level in the control pit is partly grey, as it is a period of clogging (2020-July 2021, see Appendix A). Soil moisture content at 20, 40, 60 cm depth between drains (C). Soil water potential between drains (D) and at the reference field (E). The grey blocks represent the period of water supply. Soil water potential measurements and groundwater level at the reference field are only available in 2021.

3.2. Field scale model calibration

The simulated groundwater levels and SMC from the calibrated SWAP models of field site A (Fig. 6) and C are both slightly higher and slightly lower throughout the years than the field measurements. Results from the calibrated SWAP model of field site B are comparable to the measurements of field site B. Simulated groundwater levels and SMC from the calibrated model of field site D are slightly lower than the field measurements of field site D. Subtle differences occur between measurements and model results due to differences in modelling concepts and reality and because the calibrated value represents an average value over the calibrated period while real values might differ over time, e.g. the drainage resistance (Bartholomeus et al., 2018). Statistics show that the RMSE for groundwater levels is 26.3 cm on average for all sites, ranging from 18.9 cm (site A) to 34.7 cm (site C). The RMSE for SMC is 0.05 on average for all depths at all sites. Furthermore, the RSR shows low values, indicating low RMSE values (Table 2). Finally, the KGE ranges from 0.18 (site B) to 0.66 (site A) (Table 2). Overall, simulations reproduce measurements quite well for all sites as the RMSE, RSR and KGE values indicate an acceptable model simulation performance.

The CV of calibrated parameters ranges from 2.2 % (site B) to 4.8 % (site A). The average CV of all sites is 3.6 %. Small CV values (Table C 1) show that the optimized parameters are estimated accurately (the 95 % confidence interval is small).

3.3. Field scale model validation

The simulated water supply corresponds to the measured water supply for all field sites, except in 2017 for field site A when slightly less water supply is modelled than measured (Fig. 7A). The change from fixed drainage level (in the calibration) to a dynamic drainage level (in the validation) results in a smooth water level in the control pit (Fig. 7C) followed by a smooth groundwater head (Fig. 7D). The strong decline in the water level in the control pit and thus in the groundwater head after a water supply period is also modelled quite well. Contrary, the strong rise in the water level in the control pit and thus the groundwater head at the start of the water supply period is not reproduced by the model (Fig. 7C). Nevertheless, both the modelled water supply and the level in the control pit and the groundwater level are comparable with the measurements (Fig. 7B, C, D). Furthermore, the modelled SMC at 20, 40, and 60 cm-ss is comparable to the measurements (Fig. 7E, F, G). The RMSE of WLpit is 36.2 cm on average for all sites, ranging from 27.8 cm (site B) to 44.8 cm (site C) (Table 2). The RSR is 1.15 on average for all sites, ranging from 0.89 (site D) to 1.47 (site C). The KGE varies between

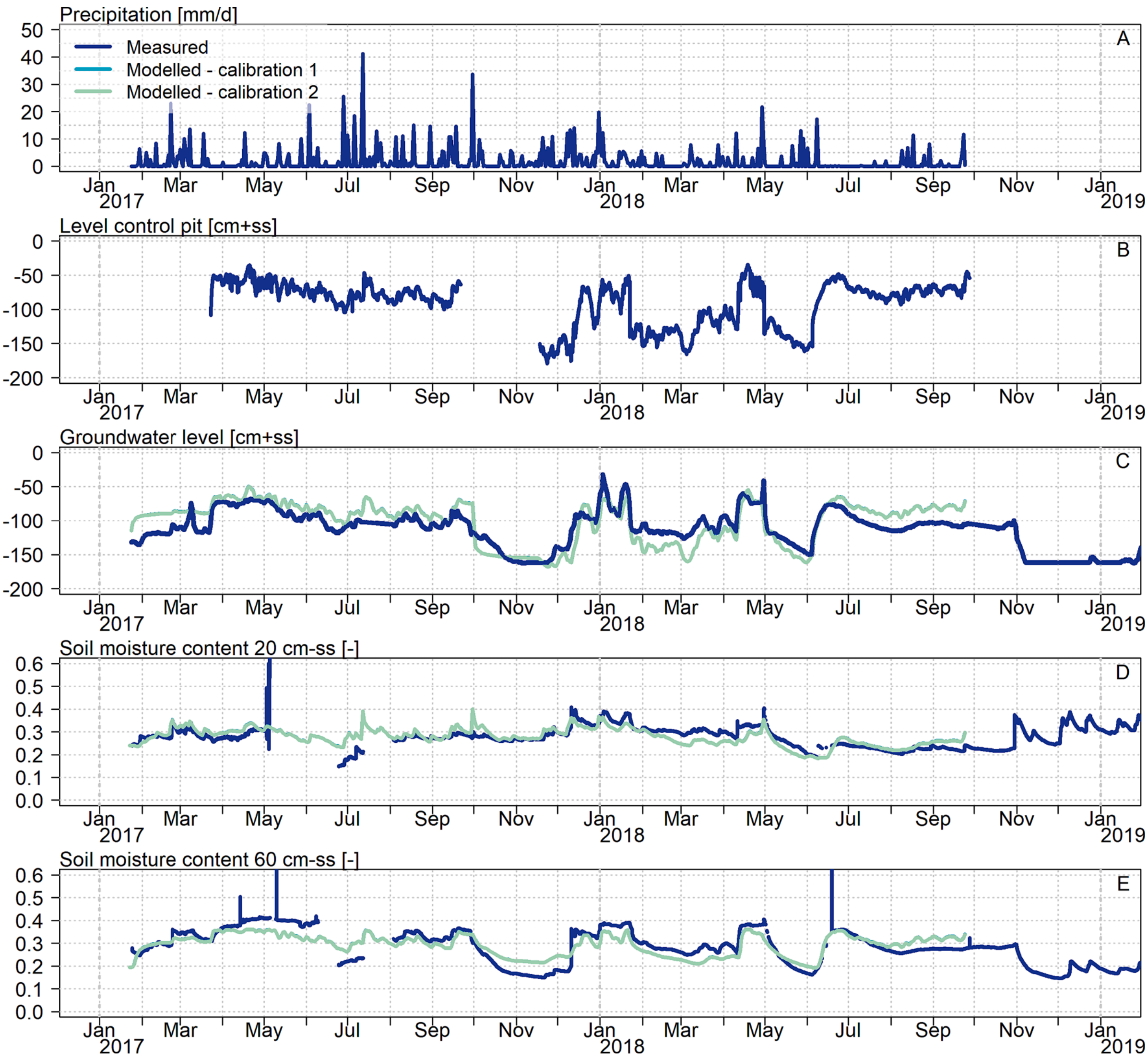

Fig. 6. Field scale calibration SWAP with PEST with the goal to optimize the soil- and hydrologic parameters for the SWAP model for field site A. Calibration is based on the measurements: groundwater level and soil moisture at 20 cm and 60 cm-ss. Calibration 1 is behind the calibration 2 line. Measured precipitation at KNMI station Arcen (number 391) (input) (A), level control pit (input) (B), groundwater level (C), soil moisture content 20 cm-ss (D) and 60 cm-ss (E).

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

	Site A			Site B			Site C			Site D*		
Parameter	RMSE	RSR	KGE	RMSE	RSR	KGE	RMSE	RSR	KGE	RMSE	RSR	KGE
GWL.cal2	18.87	0.78	0.66	20.47	1.52	0.18	34.69	0.97	0.48	31.25	1.14	0.32
SMC20.cal2	0.038	0.76	0.59	0.037	0.92	0.59	0.056	1.34	0.24	0.050	0.76	0.60
SMC40.cal2	–	–	–	0.035	1.00	0.49	–	–	–	0.090	1.19	0.33
SMC60.cal2	0.046	0.64	0.58	0.030	1.14	0.40	0.058	0.90	0.37	0.051	1.46	0.23
WLpit.val	34.33	1.11	0.25	27.80	1.14	0.49	44.78	1.47	0.12	38.02	0.89	0.29

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

0.12 (site C) to 0.49 (site B), with a mean of 0.29 for all sites. Overall, despite deviations in the water level in the control pit that affect the water supply, groundwater level and SMC, the model is still able to approach the hydrological conditions.

3.4. *General hydrologic consequences of controlled drainage with subirrigation*

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

- Wet year (Fig. 8-I): yearly precipitation is roughly 1000 mm and water supply is roughly 580 mm. Water supply only occurred in the

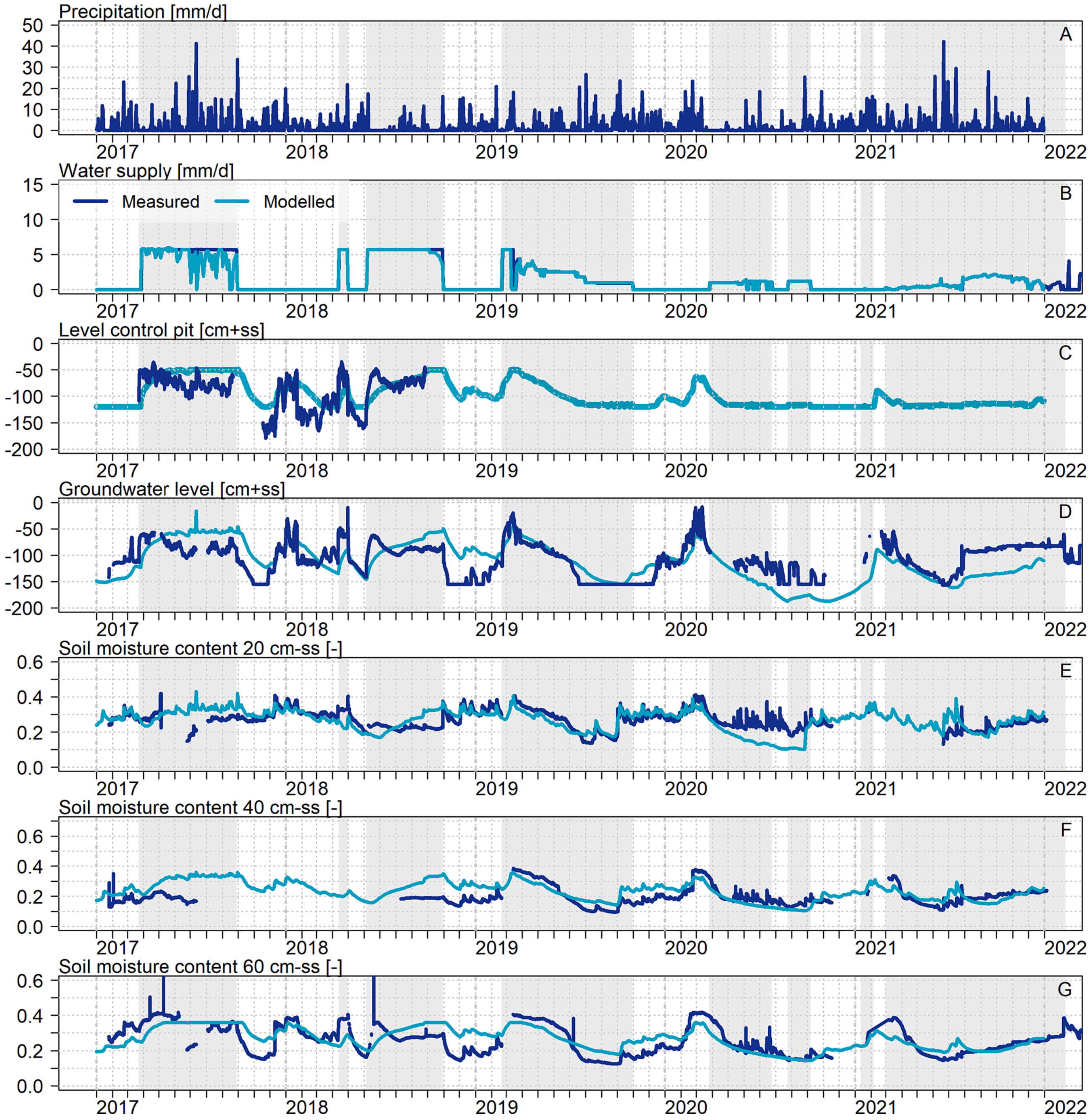

Fig. 7. Validation of the calibrated SWAP model for field site A (2017–2021). Measured precipitation at KNMI station Arcen (number 391) (A), water supply (B), water level in the control pit (C), groundwater level (D), soil moisture content 20 cm-ss (E), 40 cm-ss (F), and 60 cm-ss (G). The grey blocks represent the period of water supply.

growing season (183 days). Of these days, 125 days were at a maximum water supply (4 mm d^{-1}), for 44 days water supply was between 0.1 and 4 mm d^{-1}, and for 14 days water supply was 0 as no additional water was needed to keep the water level in the control pit at the desired level. The water level in the control pit remains quite stable throughout the year. The GWL and SMC with subirrigation are clearly higher than without subirrigation. Transpiration reduction due to drought stress is smaller with than without subirrigation. However, because transpiration reduction is already very small in the situation without subirrigation, subirrigation hardly contributes to an increased crop water availability.

- Average year (Fig. 8-II): yearly precipitation was 650 mm and water supply was 700 mm. Water supply was not at the maximum water supply during 13 days. Compared to the wet year, it takes long to raise the water level in the control pit and GWL at the start of subirrigation period (77 vs 28 days respectively). The difference in GWL between simulations with and without subirrigation is larger than in a wet year. SMC is comparable with a wet year and quite stable throughout the year. However, because transpiration reduction is still small in the situation without subirrigation, subirrigation hardly contributes to an increased crop water availability.
- Dry year (Fig. 8-III): yearly precipitation is 450 mm, water supply is 730 mm. Water supply is continuous at a maximum rate throughout the growing season. However, the maximum available water supply is not enough to raise the level in the control pit to the required 50 cm-ss. The water level in the control pit and GWL show a similar

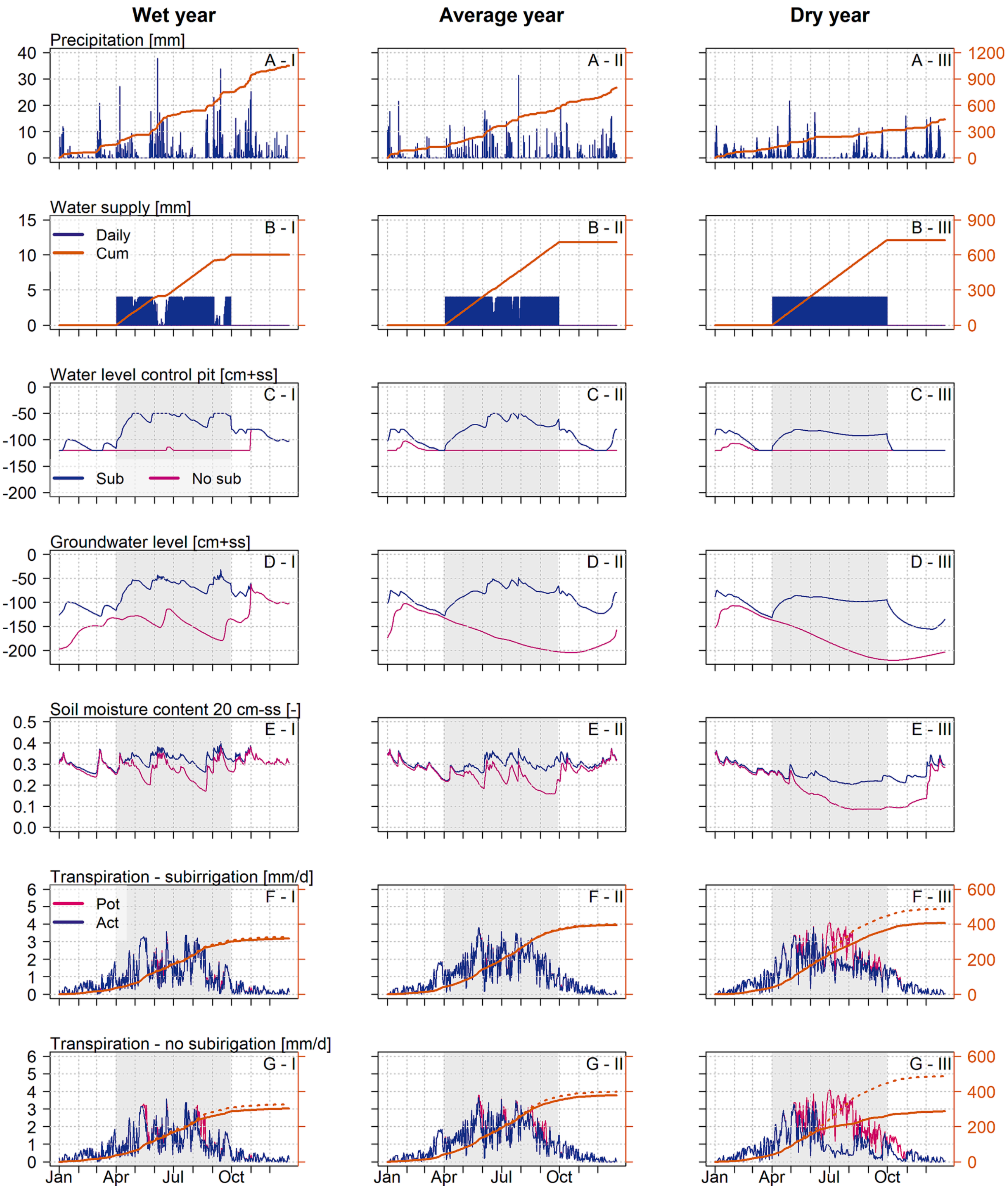

Fig. 8. Hydrological consequences of controlled drainage with subirrigation for a wet year 1998 (I, left side), an average year 2012 (II, middle) and a dry year 2018 (III, right side), as modelled with SWAP for field site A. Precipitation (input, A), water supply (modelled, B), water level in the control pit (modelled, C), groundwater level (modelled, D), soil moisture content at 20 cm-ss (modelled, E), and potential and actual transpiration for a field with subirrigation (modelled, F) and a field without subirrigation (modelled, G). Precipitation and water supply are given on daily (‘Daily’) base and cumulative (‘cum’) amounts. Transpiration is given in cumulative potential transpiration (dotted, orange lines) and cumulative actual transpiration (solid, orange lines). Water level in the control pit, groundwater level, and soil moisture content at 20 cm-ss are given for a situation without subirrigation (‘no sub’) and with subirrigation (‘sub’). The grey blocks represent the subirrigation period (1st April – 30th September).

pattern, but the level is lower than in the average year. The SMC with subirrigation is higher than without subirrigation. Actual transpiration is more than 100 mm higher due to subirrigation. However, potential transpiration is not reached. This shows that subirrigation in the dry year and with the given maximum water supply rate, was not enough to stabilize the water level in the pit and thus the groundwater level, resulting in some crop stress in July and August.

3.5. *Changes in the water balance due to subirrigation for four geohydrologic field sites*

Water balance components (Fig. 1) are strongly affected by subirrigation (Fig. 9). Changes in the water balance also depend on the meteorological conditions (wet, average or dry year). Importantly, impacts of CD-SI systems on components of the water balance are determined by the geohydrological characteristics of a field. The main changes in the water balance between a subirrigated field and a field without subirrigation are:

- Pipe infiltration increases through subirrigation. The simulated subirrigation varies between 390——600 mm in a wet year (site D vs site A) to 664 – 728 mm in a dry year (site D vs site A, dry) per growing season (183 days, April – September).
- The actual transpiration increases through subirrigation, but is strongly related to the depth of the groundwater level in relation to the rooting depth and soil properties (site specific). Capillary rise from the groundwater and rooting depth must be such that the soil water pressure head in the rooting zone is raised, resulting in an increase in root water uptake and actual transpiration. The increase in actual transpiration varies between 38 mm – 206 mm in a dry year (site B vs site C) to 0 – 14 mm in a wet year (site B vs site A). Subirrigation causes a shallower groundwater level, increasing root water uptake and crop growth.
- Downward seepage increases through subirrigation. Downward seepage increases with 131 mm – 640 mm in an average year (site C vs site B) and with 135 mm – 496 mm in a wet year (site C vs site B).
- Ditch drainage increases through subirrigation. Ditch drainage increases with 38 mm – 274 mm in an average year (site B vs site C) and with 147 mm – 336 mm in a wet year (site B vs site A). Ditch drainage occurs as the shallow groundwater level is higher than the ditch level. When subirrigation is applied, a higher shallow groundwater level will occur. Therefore, as ditch levels are kept the same, more drainage will occur. This means that water level regulation in the adjacent ditches is important to avoid unnecessary drainage.
- The exact annual effects of subirrigation on the water balance components depend on e.g. the growing season, crop development and soil moisture deficit (Fig. 9).

Part of the water supply results in a rise in GWL and an increase in SMC (Fig. 5, Fig. 7). Another part affects the water balance components (Fig. 9). However, the distribution of water supply over the water balance components differs for each field site. Fig. 10 shows the absolute changes in water balance components due to water supply for a wet, average and dry year.

- Field site A: most of the supplied water leaves the CD-SI system as ditch drainage and downward seepage (46.8 % vs 37.4 %, on average). Drainage increases more in wet years compared to dry years (56.0 % vs 33.0 %), and transpiration increases more in dry years compared to wet years (16.5 % vs 2.4 %).

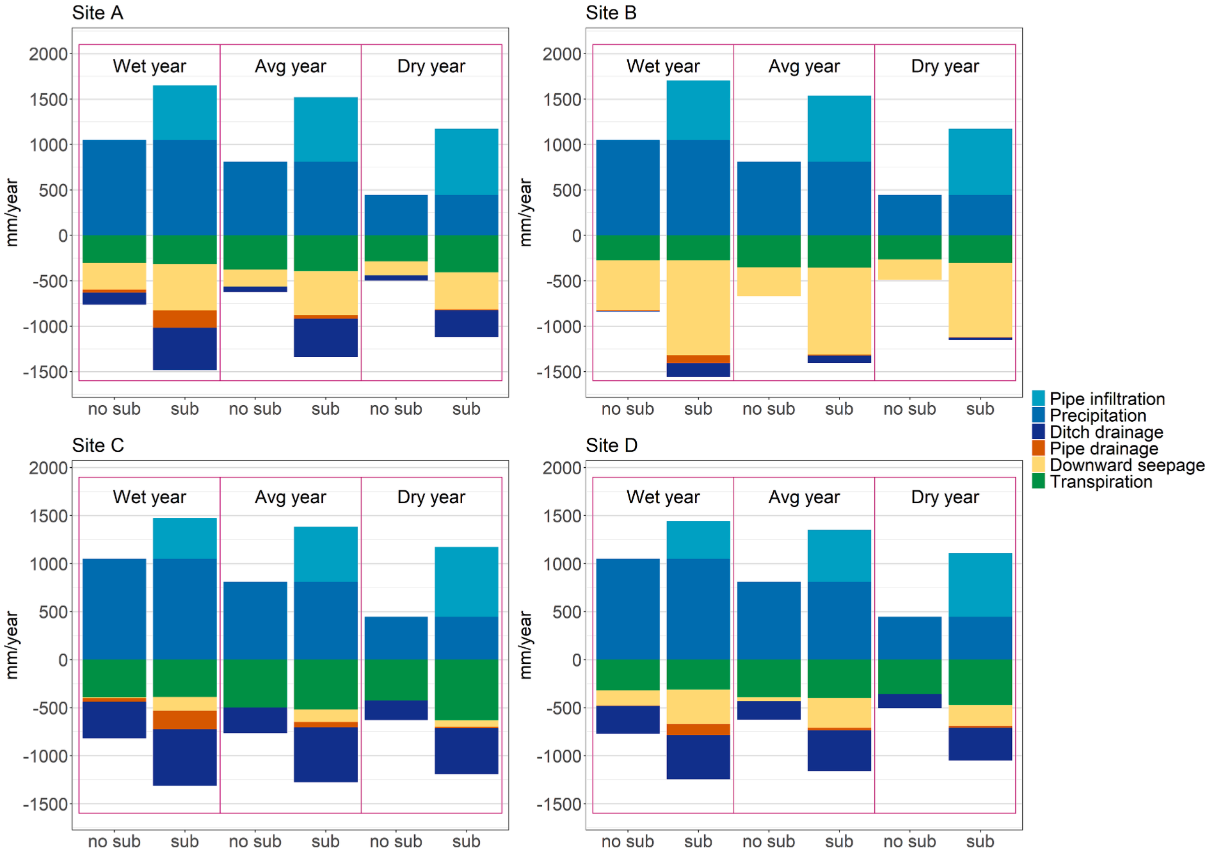

Fig. 9. The modelled water balance components with the calibrated SWAP models for the experimental sites. All components are calculated for a wet year (1998), average year (2012) and dry year (2018) for a situation without water supply ('nosub') and with water supply ('sub'). Cumulative transpiration increases with on average 0% in wet years (-2.4% – 2.4%, site A vs site D), 1.8% in average years (0.18% – 3.54%, site B vs site C), and 16.9% in dry years (5.3% – 28.4%, site B vs site C), due to subirrigation ('pipe infiltration').

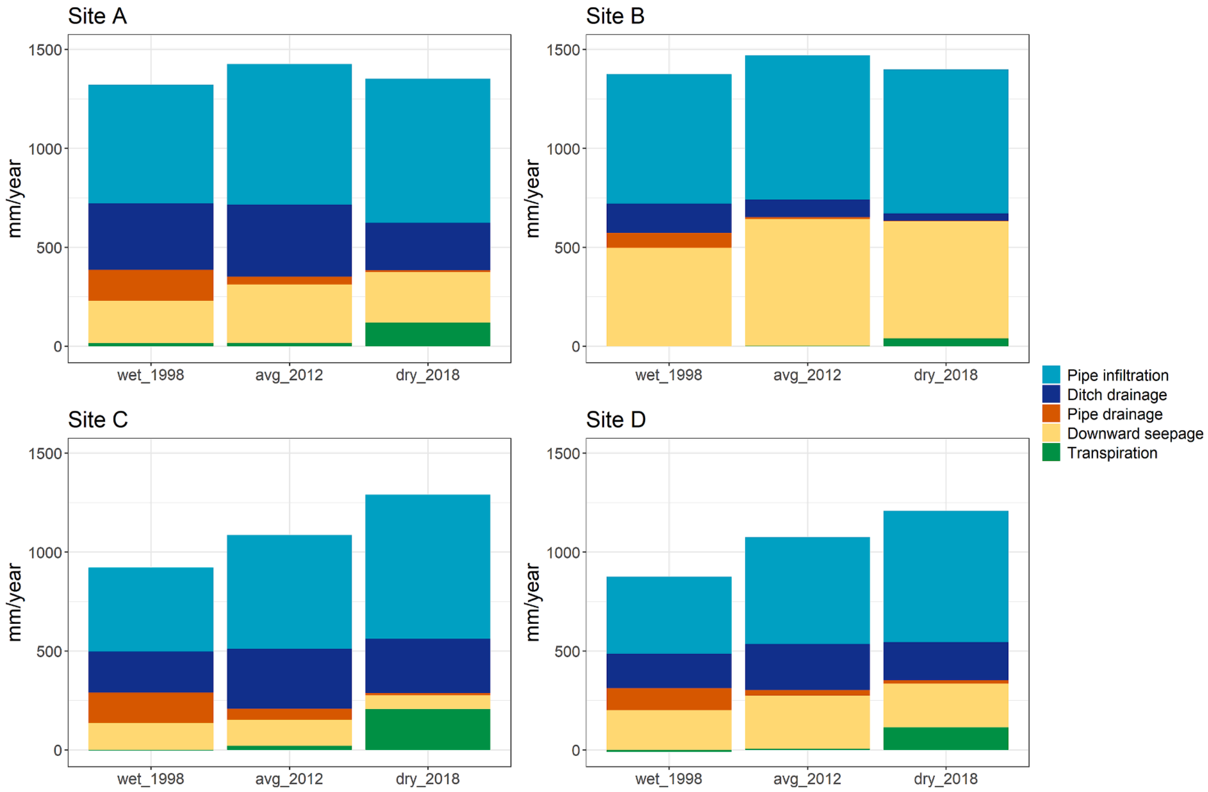

Fig. 10. The increase in water balance components (ditch drainage, pipe drainage, downward seepage and transpiration) due to subirrigation ('pipe infiltration'). The amounts are based on the modelled water balance components with the SWAP model (with subirrigation minus without subirrigation). Wet = 1998, avg = 2012, dry = 2018.

- Field site B: most water supply leaves the system as downward seepage (81.8 %, on average). There is little ditch drainage (13.3 %, on average). Transpiration especially increases in dry years (5 %) and hardly in average years (0.2 %).
- Field site C: water supply increases transpiration (10 %, on average) and ditch drainage (46.3 %, on average). The largest increase in transpiration is in the dry year (28.4 %). A part of the supplied water leaves the system as downward seepage (21.5 %, on average), as a resistance layer is present in the shallow underground. The remaining water supply leaves the system as pipe drainage (15.8 %, on average).
- Field site D: water supply leaves the system as downward seepage (44.9 %, on average), ditch drainage (38.9 %, on average), and pipe drainage (11.9 %, on average). Transpiration increases in the dry year (17.3 %) and in the average year (1.0 %).

The distribution of water supply over the water balance components differs strongly for all four sites. The geohydrological characteristics of the field site locations are the most important factor (Table 1). A lack of a hydraulic resistant (loam) layer is the reason for the large amount of downward seepage at location B. All other field locations have small loam layers in the soil which limit downward seepage (Table 1). Furthermore, ditch drainage can be avoided when the ditch level follows the groundwater level. Finally, the original mean highest and lowest groundwater level are relatively deep at field site C. Therefore, the groundwater rise as consequence of subirrigation has a large effect on the transpiration.

4. Discussion

The experiments and analysis presented in this paper are the first, to the best of our knowledge, that account for: i) comparable field set-ups of CD-SI for different geohydrological characteristics on sandy soils, ii) including an agro-hydrological simulation model to reproduce the field results and hydrological fluxes, and iii) dynamic simulation of the water supply rate and water level in the control pit. The dynamic simulation of water supply and pit water level adds complexity to the modelling approach of CD-SI systems. However, it results in a better understanding of the functioning of CD-SI systems.

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

The total amount of water used for subirrigation could be large which significantly impacts local scale hydrological fluxes (Fig. 10) and needs water supply capacity. Consequently, such a local scale measure could propagate through the regional water system. Therefore, subirrigation systems and operational management should be implemented in such a way that they fit within both the local and regional management (Fig. 11) and that they match fresh water availability. The modelling procedure developed in this study could be used to identify appropriate field sites for CD-SI application and the hydrological consequences

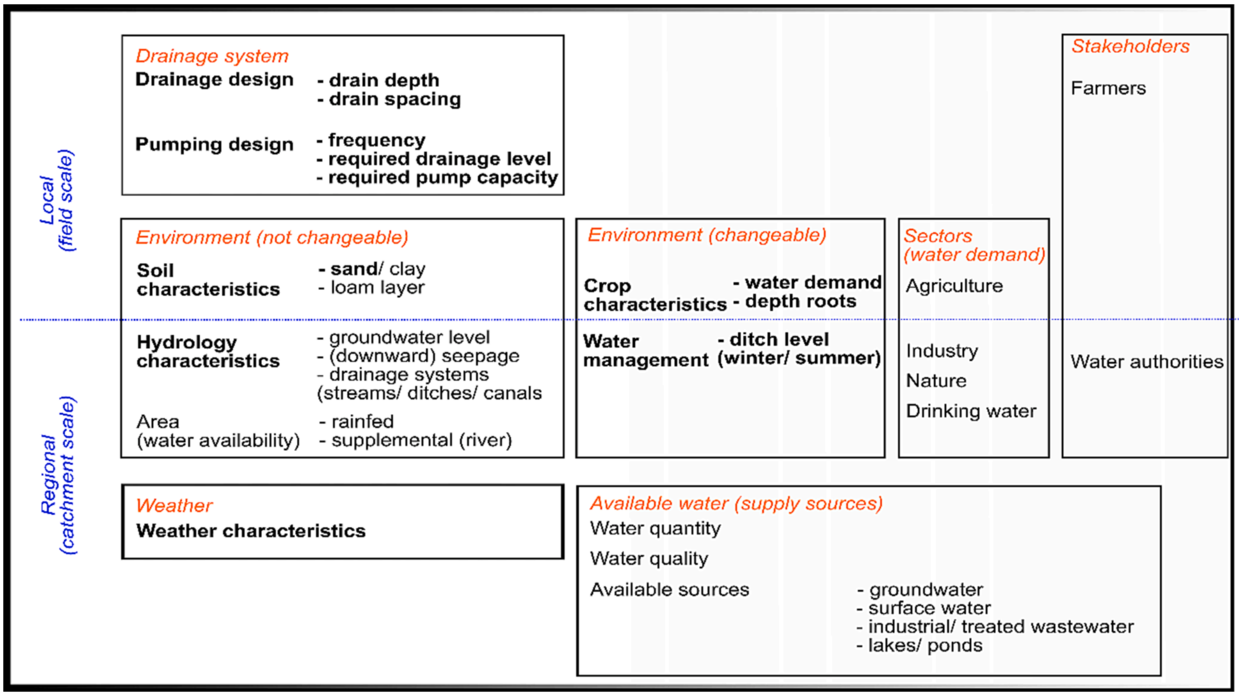

Fig. 11. Overview of local and regional scale components to take into account when implementing controlled drainage with subirrigation. The components in bold are part of the field experiments and modelling analysis. Figure adapted from De Wit et al. (2022).

before implementing subirrigation. All aspects related to drainage design, required water supply, and field scale impact could be modelled with SWAP. This includes explorations on the effect of subirrigation for different crops and crop characteristics. As example we analysed the effect of subirrigation for a rooting depth for grass of 50 cm instead of 30 cm (as used in this study; schematization of site A). This 20 cm increase in rooting depth increased plant transpiration in the dry year with 5.6 %. The increase in transpiration results in a decrease in lateral drainage (−4.4 %), downward seepage (−2.0 %) and pipe drainage (−1.1 %). This means a larger portion of the subirrigated water contributes to crop growth, while less water is drained to the groundwater and surface water system. Similar analysis could be done with e.g. drainage design (drain depth and drain spacing), water supply design (frequency, required drainage level and capacity), soil type, resistance to downward seepage, surface water management and crop type, for all possible meteorological conditions (Fig. 11).

Required water supply and e.g. increased downward seepage (i.e. increased groundwater recharge) are relevant for the regional implementation of CD-SI with subirrigation. The scheme presented in Fig. 11 provides an overview of considerations to take into account.

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

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

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

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

5. Conclusion

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

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

CRediT authorship contribution statement

Janine A. de Wit: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Marjolein H.J. van Huijgevoort:** Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Jos C. van Dam:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Supervision. **Gé A.P.H. van den Eertwegh:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Dion van Deijl:** Investigation, Writing – review & editing. **Ruud P. Bartholomeus:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision.

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

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

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Appendix A. Supplementary data

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