Subsurface Irrigation in Regional Water Management: a System Dynamics Approach to Support Decision Making

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Abstract

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

Keywords Controlled drainage · Local scale · Regional scale · Subirrigation · System dynamics modelling · Vensim · Water management.

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1 Introduction

The mismatch between water demand and supply is increasing due to climatic and socioeconomic changes (Pronk et al. 2021). In temperate climates, regional water management strategies are therefore shifting from exclusively drainage, to drainage, retention and recharge (Bartholomeus et al. 2023). This shift is also reflected at the local scale where conventional drainage systems, historically installed to discharge water during wet periods (De Wit et al. 2022) are changed to controlled drainage (CD) systems that both retain and discharge water, and to controlled drainage with subirrigation (CDSI) systems (Fig. 1), which can retain, recharge, and discharge water.

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

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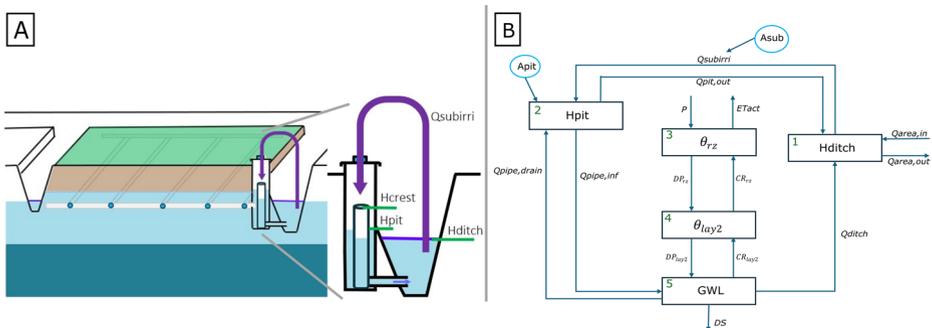

Fig. 1 A: Schematization of a CDSI system with the infiltration/drainage pipes in grey (dotted) lines. **B**: CDSI in a system dynamics approach with state variables (square), hydrological fluxes (arrows) and scaling factors (circle)

Hydrological models range from detailed spatially distributed models to black box models, with lumped approaches in between. Spatially distributed models are most suitable for detailed analyses, such as identifying exact locations for upscaling CDSI. Lumped system dynamics models (SDMs) are useful for initial assessments of the feasibility of implementing a measure (Zhou et al. 2025); in this study, an SDM is applied to assess the upscaling of CDSI in relation to its impact on the magnitude of hydrological fluxes. SDMs are particularly valuable for understanding non-linear behavior of interactive, complex systems, and for supporting policy decisions and system design (Javanbakht-Sheikhhamad et al. 2024; Mashaly and Fernald 2020; Phan et al. 2021). SDMs are extensively used for rainfall-runoff modelling (Brauer et al. 2014), but can also simulate groundwater systems if hydrological properties are well conceptualized (Ejaz et al. 2022). However this has rarely been done (Phan et al. 2021). SDMs have been applied to simulate hydrological fluxes related to irrigation (Khan et al. 2009) and related to subsurface drainage systems combined with irrigation (Matinzadeh et al. 2017). To the best of our knowledge, no SDM has yet been developed to assess the regional upscaling of CDSI, despite the fact that both the non-linear effects of upscaling and the need for decision support tools call for such a novel approach. Therefore, the aim of this study is to (i) investigate to what extent regional upscaling of CDSI can be supported using an SDM in relation to surface water availability and (ii) identify how an SDM can support water management authorities in decision making.

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

2 Methods

2.1 General CDSI Setup in SDM Based on an Experimental Site

The general setup of the SDM for regional evaluation of CDSI upscaling includes the key elements and hydrological fluxes influenced by a CDSI system embedded within a regional context (Fig. 1). In general, a CDSI system consists of a control pit where external water (from a ditch) for subirrigation is supplied. The control pit is connected to a collector pipe, which is in turn connected to the infiltration/drainage pipes, which is oriented perpendicular to the collector pipe. Water flows through the pipes and enters the groundwater via perforated holes. Soil moisture reaches the plant rooting zone through capillary rise from the groundwater. Therefore, the SDM contains the water reservoirs 'ditch' (1), 'control pit' (2), 'groundwater' (5), 'rooting zone' (rz, 3) and 'second layer of the unsaturated zone' (lay2, 4) (Fig. 1). These reservoirs are connected via flows to simulate the hydrological fluxes. Finally, a scaling factor is included to upscale the CDSI covered area within the SDM.

The SDM is programmed in Vensim (version: Vensim PLE Plus 9.0.1 × 64). System components are described as state variables connected by hydrological fluxes and supported by auxiliary variables (e.g. wilting point, drain spacing). The SDM is based on a field study conducted in the southeast of the Dutch sandy Pleistocene uplands (51º27'N, 5º57'E) where

CDSI was applied between 2017 and 2024. This field experiment was used as a base because (i) the hydrological consequences of CDSI on field scale were known in detail for this location (De Wit et al. 2024b), (ii) the location is a field site with average suitability for subsurface irrigation in terms of geohydrological characteristics in the sandy Pleistocene uplands of the Netherlands (De Wit et al. 2024b), and (iii) there are discussions between local and regional stakeholders on the risks and benefits of regional CDSI upscaling.

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

2.2 CDSI Schematisation in Vensim

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

2.2.1 Regional Water Management

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

$$H_{\text{ditch,t}} = H_{\text{ditch, t-1}} + \frac{Q_{\text{ditch,t}} + Q_{\text{area\_in,t}} + Q_{\text{pit\_out,t}} - Q_{\text{area\_out,t}} - Q_{\text{subirri,t}}}{A_{\text{ditch}}} \quad (1)$$

where $H_{\text{ditch, t-1}}$ is ditch level at timestep t-1 (m), Q_{ditch} is ditch drainage (m^3), $Q_{\text{area\_in}}$ is regional inflow (m^3), $Q_{\text{pit\_out}}$ is water drained from the pit to the ditch (m^3), $Q_{\text{area\_out}}$ is regional outflow (m^3), Q_{subirri} is water abstracted for subirrigation (m^3), A_{ditch} is ditch area (m^2). Surface water exits the ditch as subirrigation or outflow over the weir. H_{ditch}

raises through regional inflow or through ditch drainage. Q_{subirri} occurred from 1st April to 30th September when $GWL < GWL_{\text{pref}}$ and when $H_{\text{ditch}} > H_{\text{ditch\_min}}$, i.e. when surface water is available as source for subirrigation.

2.2.2 CDSI Systems: Control Pit

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

$$H_{\text{pit,t}} = H_{\text{pit, t}-1} + \frac{Q_{\text{pipe\_drain,t}} + Q_{\text{subirri,t}} - Q_{\text{pit\_out,t}} - Q_{\text{pipe\_inf,t}}}{A_{\text{pit}}} \quad (2)$$

where $H_{\text{pit,t}-1}$ is level in the control pit at timestep t-1 (m), $Q_{\text{pipe\_drain}}$ is pipe drainage (m³), Q_{subirri} is water supply (m³), $Q_{\text{pit\_out}}$ is pit drainage (m³), $Q_{\text{pipe\_inf}}$ is pipe infiltration (m³), A_{pit} represents the total area in the underground system where subirrigation is applied, including the pit, pipes and soil around the pipes. A_{pit} is estimated as $A_{\text{pit}} = 0.19 * A_{\text{sub}}$ (m²), where A_{sub} is the area with CDSI fields (m²). The factor 0.19 was estimated based on manual calibration of the simulated H_{pit} to the measured H_{pit}. Furthermore, H_{pit} is controlled via the crest height (H_{crest}). The control pit retains groundwater when $H_{\text{pit}} < H_{\text{crest}} \& Q_{\text{subirri}} = 0$, recharges groundwater when $H_{\text{pit}} < H_{\text{crest}} \& Q_{\text{subirri}} > 0$, and discharges water when $H_{\text{pit}} > H_{\text{crest}}$.

2.2.3 Rooting Zone

The soil water system was split into the rooting zone, the second layer of the unsaturated zone and the saturated zone. The soil moisture content in the rooting zone (θ_{rz}) (m³/m³) is estimated as:

$$\theta_{\text{rz,t}} = \theta_{\text{rz,t}-1} + \frac{P_t + CR_{\text{rz,t}} - ET_{\text{act,t}} - DP_{\text{rz,t}} - Q_{\text{pond,t}}}{Dr_{\text{rz}} * A_{\text{sub}}} \quad \theta_{\text{wp}} < \theta_{\text{rz}} < \theta_{\text{sat}} \quad (3)$$

where $\theta_{\text{rz,t}-1}$ is the SMC in the rooting zone at timestep t-1 (m³/m³), P is precipitation (m³), CR_{rz} is capillary rise from the second layer to the rooting zone (m³), ET_{act} is actual evapotranspiration (m³), DP_{rz} is deep percolation from the rooting zone to the second layer (m³), Q_{pond} is ponding layer that disappears as runoff (m³), Dr_{rz} is the rooting zone depth (m). Furthermore, ET_{ref} was multiplied by a crop factor to calculate potential evapotranspiration (ET_{pot}). Next, ET_{pot} was multiplied by a reduction factor for reduced root water uptake due to water limitation, to calculate ET_{act}. As a linear relationship is assumed between relative transpiration and relative crop yield (De Wit 1958), $ET_{\text{act}} < ET_{\text{pot}}$ indicates that crop water demand cannot be met and thus drought stress occurs.

2.2.4 Second Unsaturated Zone Layer

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

$$\theta_{\text{lay2,t}} = \theta_{\text{lay2,t}-1} + \frac{\text{CR}_{\text{lay2,t}} - \text{CR}_{\text{rz,t}} + \text{DP}_{\text{rz,t}} - \text{DP}_{\text{lay2,t}}}{Dr_{\text{lay2,t}} * A_{\text{sub}}} \quad \theta_{\text{wp}} < \theta_{\text{lay2}} < \theta_{\text{sat}} \quad (4)$$

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

2.2.5 Saturated Zone

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

$$GWL_t = GWL_{t-1} + \frac{DP_{\text{lay2,t}} + Q_{\text{pipe\_inf,t}} - CR_{\text{lay2,t}} - Q_{\text{ditch\_drain,t}} - Q_{\text{pipe\_drain,t}} + DS_t}{A_{\text{sub}}} * \frac{1}{S} \quad (5)$$

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

2.2.6 Scaling Area with CDSI

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

2.3 Field Scale Model SWAP To Validate SDM

The SDM results of the base run were compared to the SWAP results (De Wit et al. 2024b) using the Kling-Gupta efficiency (KGE, Gupta et al. (2009) and root mean square error (RMSE). SWAP is a 1D, process-based numerical model combining soil water flow (unsaturated zone, saturated zone and drainage management), root water uptake and crop growth, focusing on field scale. The parameterization of the SWAP model of De Wit et al. (2024b), calibrated and validated against field measurements, was slightly modified to allow comparison to the SDM. With respect to the published SWAP modeling, this includes changes in H_{crest}, H_{ditch}, soil profile (homogeneous O02 soil, Heinen et al. (2020), the soil evaporation coefficient of Black was set to 0.80 and critical limits for root water uptake according to Feddes (1982) were set to h$_1$ = 100 cm, h$_2$ = 0 cm, h$_3$ = −100 cm, h$_4$ = −16000 cm.

2.4 Scenarios

CDSI was simulated using varying implementation scales of subirrigation, combined with subtle differences in geohydrological characteristics. First, the percentage of subirrigation

of the total area is adjusted from 1.08% (field experiment area) to 10%, 20%, 25%, 40%, 50%, 60%, 80%, 90% and 99% with the goal to understand the propagation of CDSI effects through different components of the water system and the effect of upscaling. All other scenarios are simulated with 50% subirrigation of the total area. These scenarios use the following values: (i) inflow of surface water into the ditch to increase regional water availability: 2000 m³/d, 3000 m³/d, 4000 m³/d, 5000 m³/d and 6000 m³/d; (ii) drainage resistance to the ditch: 350 d, 500 d, 650 d, 800 d, 1000 d, 1200 d; (iii) weir height (H_{weir}): 1.5 m-ss, 1.3 m-ss, 1.1 m-ss, 0.9 m-ss, 0.7 m-ss and 0.5 m-ss to drain less groundwater and increase water storage in the ditch; (iv) minimum H_{ditch}: 1.9 m-ss, 1.7 m-ss, 1.5 m-ss, 1.3 m-ss, 1.1 m-ss, 0.9 m-ss, 0.7 m-ss and 0.5 m-ss. H_{weir} was set to 0.5 m-ss for the H_{ditch} scenarios; (v) preferable GWL for subirrigation: 1.3 m-ss, 1.1 m-ss, 0.9 m-ss, 0.8 m-ss, 0.7 m-ss, 0.5 m-ss. These scenarios were primarily aimed at indicating the hydrological effects of CDSI upscaling. The variation due to differences in geohydrological characteristics within a scenario can be interpreted as a sensitivity analysis.

3 Results

3.1 SDM and SWAP Modelling of CDSI Systems on a Local Scale

The measured precipitation ranges between 700 and 800 mm in 2013–2017 and 2021 and ranges between 445 and 602 mm in the drier years 2018–2020, 2022 (Fig. 2A). Simulated annual subirrigation ranges from 525 mm in 2016 to 665 mm in 2022, depending on yearly meteorological conditions. The KGE was 0.95 and the RMSE 31.9 mm (Fig. 2A) indicating acceptable model performances.

H_{pit} (Figure SM2D) and GWL are raised with roughly 1 m due to subirrigation in both the SDM and SWAP model (Fig. 2B). In the SDM, the water levels stabilize around 0.8 m-ss in summertime due to the set preferable GWL of 0.8 m-ss, the water levels fluctuate in wintertime due to alternating water retention and discharge. In general, water levels simulated with SWAP show more meteorological fluctuations compared to water levels in SDM, resulting in a KGE of 0.28 and a RMSE of 0.19 m. This is possibly due to the calculation procedure of percolation and capillary rise in the SDM. However, the magnitude of the water levels simulated by the SDM is comparable to those simulated by SWAP, which is important for the calculation of the head differences between groundwater and surface water due to subirrigation.

ET_{act} increases due to subirrigation as a consequence of higher GWL, due to capillary rise and higher soil moisture availability in the root zone, as simulated by both the SDM and SWAP. The annual ET_{act} ranged from 300 to 600 mm in both the SDM and SWAP simulations (Fig. 2C), depending on annual meteorological conditions. No drought stress develops in the average and wet years 2013–2017 and 2021. In dry years (2018–2020, 2022), ET_{act} increases with roughly 40% due to subirrigation, although some drought stress occurs (Fig. 2A, C). Both KGE and RMSE values indicate acceptable model performances.

Larger head differences between GWL and H_{ditch} due to subirrigation increase ditch drainage and downward seepage (Figure SM2). Water for subirrigation is abstracted from the surface water, lowering H_{ditch}, but increasing ditch drainage, which results in a return flow to the surface water. Thus, the net use of surface water for CDSI is reduced due to
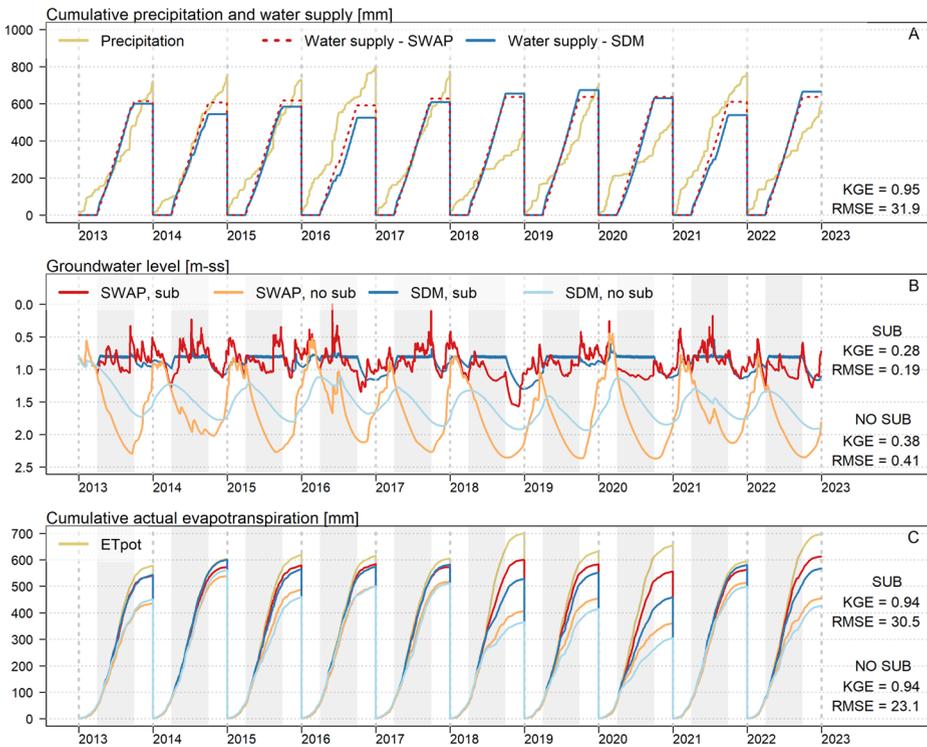
Fig. 2 Overview of measured precipitation of the weather station Arcen and modelled subirrigation (**A**), groundwater level (**B**) and actual evapotranspiration (**C**). All components are simulated with both the lumped SDM and the agro-hydrological model SWAP, for situations with ('sub') and without ('no sub') subirrigation. The grey areas represent subirrigation periods. Statistics Kling-Gupta Efficiency (KGE) and Root Mean Squared Error (RMSE) are used to evaluate the performance of the SDM compared to the SWAP model. In conclusion, SDM captures the subirrigation patterns of the SWAP-model, which was calibrated against field measurements

increased ditch drainage, a process captured by the SDM. Pipe infiltration shows an instable/peaky pattern in summertime due to interacting process of surface water use, subirrigation raising groundwater levels and resulting increased ditch drainage. Finally, the mass water balance values of all individual reservoirs are checked and are in an acceptable range.

3.2 Hydrological Consequences of CDSI Upscaling Using a Lumped SDM

CDSI upscaling affects hydrologic fluxes, but is strongly limited by the regional water availability. Upscaling CDSI means that the regional water inflow remains the same while the total amount of applied water for subirrigation increases as long as sufficient surface water is available (Fig. 3A). Model results show that subirrigation increases from 600 mm/y to 700 mm/y when CDSI is upscaled from 1% to 25% of the total area. More water supply decreases H_{ditch} from 1 m-ss to 1.5 m-ss, resulting in increased ditch drainage. When CDSI is further upscaled to 50% and 80%, subirrigation decreases to 600 mm/y and 400 mm/y respectively. This is due to H_{ditch} reaching the minimum required level, which limits
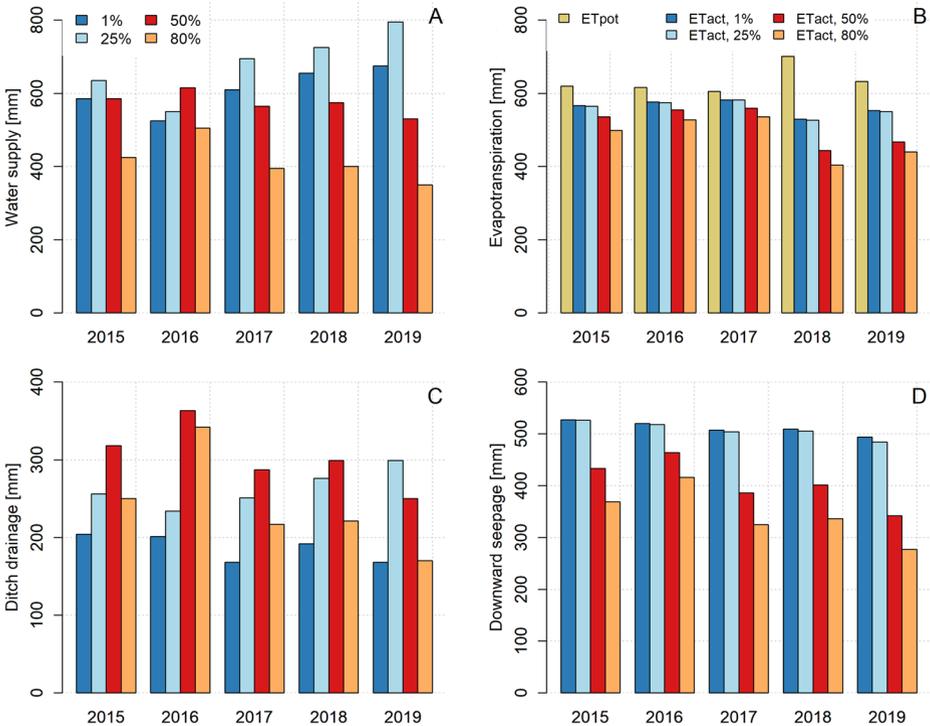
Fig. 3 Overview of water supply (**A**), actual evapotranspiration (**B**), drainage to the ditch (**C**) and downward seepage (**D**) simulated with the lumped system dynamics model. All components are calculated using the model, including subirrigation ('sub'), for scenarios where 1%, 25%, 50% or 80% of the area applies subirrigation. In conclusion, CDSI upscaling affects almost all hydrological fluxes, but is strongly related to regional water availability

water availability for subirrigation. As a result of reduced subirrigation, ET_{act} decreases to 600 mm/y – 400 mm/y (Fig. 3B). Groundwater levels are lowest and crop water stress is highest for higher percentages of upscaling (Figure SM3), indicating that regional water supply is insufficient to meet the CDSI requirements. Water exits the system as ditch drainage and downward seepage (Fig. 3C, D). Ditch drainage varies between 0.7 mm/d and 3 mm/d depending on the head differences between GWL and H_{ditch} (Figure SM3). Due to the head difference, ditch drainage initially increases with higher percentages of upscaling, even though the required groundwater levels cannot be met, which is visible in the decrease in ET_{act}. However, beyond 50% upscaling, ditch drainage decreases because the GWL lowers. This is caused by limited water availability for supply, resulting in a small head difference between GWL and H_{ditch}. Nevertheless, head differences still increase due to low surface water levels, showing the feedbacks involved in regional CDSI implementation. At the highest values of upscaling, insufficient water is available for subirrigation due to over-exploitation of surface water, leading to lower groundwater levels, and, consequently lower ET_{act}, ditch drainage and downward seepage.

Because meteorological conditions propagate through the entire soil water system, the need for subirrigation in the 50% scenario is lower in the wet year 2016 than in drier years.

This also results in a higher H_{ditch} in 2016 compared to 2015 and 2017–2019 and a *GWL* close to the preferable *GWL* until August 2016. Furthermore, the lumped SDM is able to simulate the effects of heavy rainfall in June 2016 as a strong raise in GWL and Q_{ditch} occurs, resulting in a period of no subirrigation and more downward seepage (Figure SM3). Conversely, in the dry years 2018–2019 insufficient surface water is available to raise the *GWL* to the preferable *GWL* for the 50% and 80% subirrigation scenario (Figure SM3). As a result, ET_{act} decreases, drought stress develops and ditch drainage declines throughout the summer (Fig. 3C, Figure SM3). Thus, the SDM is able to simulate the consequences of meteorological conditions on the propagation and effectiveness of CDSI upscaling.

Upscaling of CDSI shows non-linear effects in hydrological fluxes, in which three distinct phases can be distinguished, demonstrated for 2018 (Fig. 4). First, from 1% to 20% CDSI area, subirrigation and Q_{ditch} increase (with 30 mm and 31 mm respectively) while H_{ditch} slightly decreases (0.12 m) and ET_{act} and *DS* remain roughly the same. This means that sufficient surface water is available to upscale CDSI to 20%, with little impact on the regional surface water availability. Second, from 20% to 30% CDSI area, subirrigation and Q_{ditch} increase (70 mm and 140 mm respectively), while H_{ditch}, ET_{act} and *DS* decrease (0.42 m, 4 mm and 26 mm respectively). This means that sufficient water is available to upscale CDSI to 30%, but H_{ditch} drops sharply, which increases Q_{ditch}, causing an increase in the water demand for subirrigation to reach the desired *GWL*, further enhancing the impact on regional water availability. Third, from 30% to 99% CDSI area, Q_{subirri}, Q_{ditch}, ET_{act} and *DS* decrease (430 mm, 141 mm, 109 mm, 177 mm respectively), as
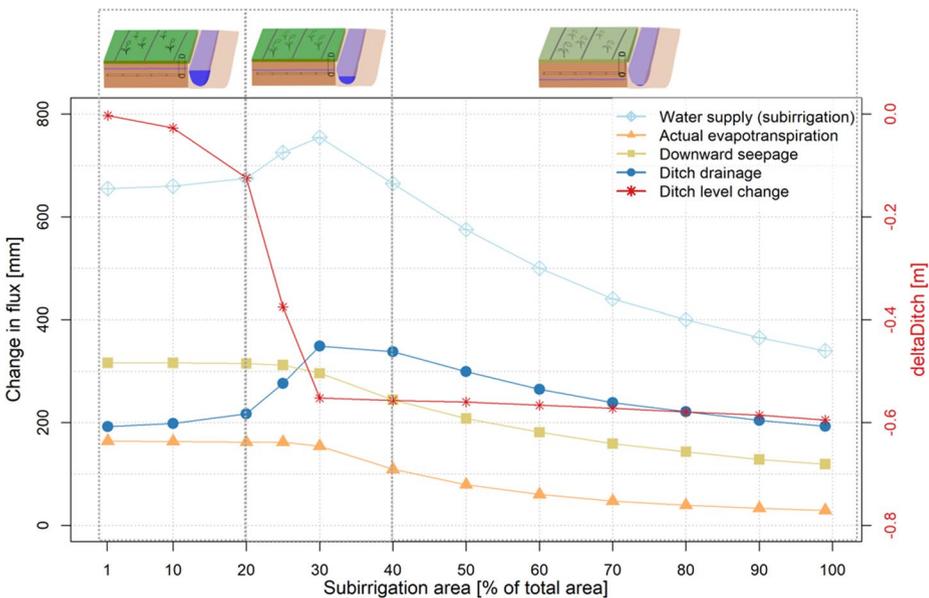

Fig. 4 The increase in the hydrological fluxes water supply, actual evapotranspiration, downward seepage and ditch drainage based on SDM simulations (subirrigation minus no subirrigation) as well a change in ditch level (maximum minus minimum per simulation, 'deltaDitch', right y-axis) are shown as function of the percentage of the total area applying subirrigation ('subirrigation area') for the year 2018. In conclusion, CDSI upscaling shows non-linear propagation in hydrological fluxes, in which three phases could be identified

surface water availability limits the amount of subirrigation. ET_{act} increase reduces with 80% between 30% and 99% area of CDSI to about 27 mm increase in ET_{act} compared to a situation without subirrigation, which makes subirrigation likely unbeneficial. When subirrigation would still be applied for this specific situation, this would not improve crop water availability and negatively impacts surface water level. In conclusion, three critical phases related to regional water availability determine the possibilities for CDSI upscaling. It is crucial to identify which phase the effects of upscaling correspond to: from Phase 1, with sufficient regional water availability; through Phase 2, a critical zone where water demand begins to limit regional availability; to Phase 3, where high water demand significantly impacts the regional water system and CDSI is no longer beneficial for the crop.

Limitations imposed by the regional water availability strongly depend on geohydrological characteristics, field scale water management and regional water management. A key geohydrological characteristic is the drainage resistance towards the ditch, which also reflects the orientation of the CDSI fields: fields oriented perpendicular to the ditch have a higher drainage resistance than those parallel to it. Field water management is characterized by the preferable GWL for crop growth. Regional water management determines the inflow to the regional surface water, weir management and minimal required H_{ditch}. In general, measures to increase regional surface water availability, may provide more opportunities for CDSI upscaling and thus subirrigation, which raises the GWL and increases ET_{act}, DS and Q_{ditch} (Fig. 5). Furthermore, a lower preferable GWL or higher drainage resistance to the ditch ensures that less water is needed to meet the preferable GWL and, as a result, more water remains regionally available (Fig. 5). Therefore, the limitations of upscaling CDSI depend on both the regional water management by the water authorities and the water management by the farmer.

4 Discussion

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

A major challenge in the Netherlands is the distribution of water through the regional water system, that supports both nature and the anthropogenic water demands of various sectors, which often compete for similar water sources. Hydrological consequences of
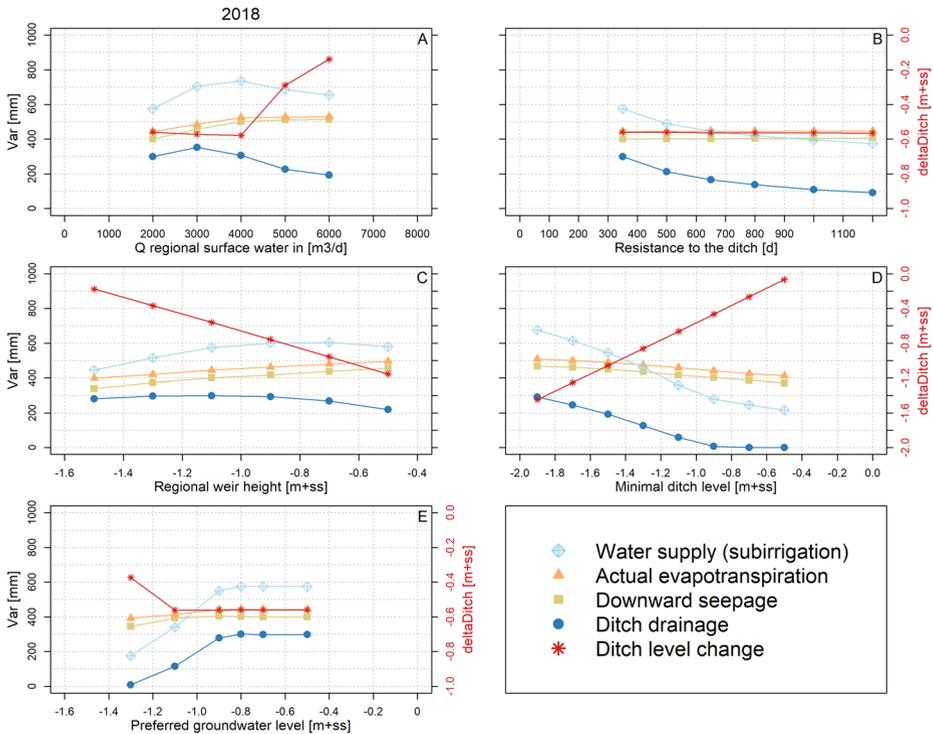
Fig. 5 Simulated hydrological fluxes subirrigation, actual evapotranspiration, downward seepage and ditch drainage as well as change in ditch level (annual maximal minus minimum 'deltaDitch', right y-axis) as function of regional inflow of surface water (**A**), resistance to the ditch (**B**), regional weir height (**C**), minimal ditch level (**D**) and preferable groundwater level (**E**). All simulations assume that 50% of the total area applies subirrigation for 2018. Base input for all scenarios includes 2000 m³/d surface water inflow, a weir height of 1.1 m-ss, minimal ditch level of 1.6 m-ss (with a weir height of 0.5 m-ss), a preferred GWL of 0.8 m-ss unless the respective variable was modified. In conclusion, limitations in regional water availability for CDSI upscaling to 50% depend strongly on geohydrological characteristics, local scale water management and regional water management

CDSI at one single field cannot be extrapolated linearly to a larger area, because the hydrological consequences of upscaling CDSI involve non-linear feedbacks. The SDM approach is able to capture and visualize these feedbacks. Thus, using an SDM, water management authorities could obtain insight into the balance between water availability and the potential for upscaling CDSI within a region. This can be particularly useful in the early stages of strategic area planning, when optional measures are being explored. In Fig. 4, insufficient water is available to implement CDSI in more than 40% of the area. Depending on site suitability and regional water availability for subirrigation, controlled drainage could be converted to CDSI, or it may be decided not to support the implementation of CDSI to mitigate water stress.

An SDM approach is a simple but comprehensive tool that uses concise equations to approximate the results of a more complex model (Khan et al. 2009). This comes with both strengths and limitations. The lumped SDM is designed such that it is transparent, and makes it relatively easy to understand the system and impacts of management scenarios.

Subsystems (and equations) can easily be added. However, it should always be considered whether adding complexity contributes to improved understanding (Wagener et al. 2001).

The main strengths of the developed SDM are the interactions between the important CDSI subsystems. First, the net effect of subirrigation on surface water levels is key in CDSI upscaling. Second, while the interaction between the *GWL* and unsaturated zone by CDSI is crucial for understanding crop water availability, it has been insufficiently addresses in other literature. This study contributes to the literature by including this interaction into an SDM setup. Conversely, a limitation of the SDM could be that a lumped model provides integral results in the order of magnitude of hydrological fluxes and water levels, rather than spatially explicit impacts at specific fields. Second, the SDM simplifies soil water flow by assuming instantaneous water redistribution in its reservoirs, whereas numerical models such as SWAP solve the Richards equation to simulate gradual vertical flow in the unsaturated zone. This may lead to an overestimation of upward and downward water flow rates in the unsaturated soil, resulting in more stable groundwater levels rather than fluctuations due to precipitation and evapotranspiration (Fig. 2). However, the simulated *GWL* using the SDM shows a RMSE of 0.19 m compared to SWAP and, given that the magnitude of water levels and hydrological fluxes is key in this study, the model appears to be a valid approach. Third, given the lack of studies in which CDSI is upscaled, we initiated this study with a base SDM representing a single field (1% of the area) to assess the plausibility of using an SDM. The outcomes of the SDM were compared with the results of the agro-hydrological model SWAP, which was calibrated against field measurements. CDSI was then upscaled, assuming uniform soil and crop characteristics across the region. De Wit et al. (2024a) shows that increasing the rooting depth from 30 to 50 cm reduces the water demand for subirrigation. For this study, it implies that due to the limited rooting depth the subirrigation demand might be slightly overestimated. Although the aim of this study was to present a methodology to efficiently explore the feasibility of CDSI upscaling, in further applications of the SDM varying soil or crop characteristics can be included.

5 Conclusion

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

CDSI upscaling showed non-linear propagation in hydrological fluxes in which three phases can be identified: (1) sufficient surface water is available for CDSI upscaling, with minimal impact on regional surface water availability, (2) sufficient water is available for upscaling, but the surface water level drops sharply, increasing the impact on regional water availability and (3) surface water availability becomes a limiting factor for subirrigation,

restricting crop water availability and putting a large pressure on regional surface water levels. Furthermore, limitations by regional water availability strongly depend on geohydrological characteristics and regional water management, meaning that the effects of CDSI upscaling depend on both the regional strategies by water management authorities and practices by farmers. Understanding the consequences of upscaling CDSI is important for water management authorities in the strategic planning of regional development.

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

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Data Availability All data and materials used in this study are valuable on request.

Declarations

Ethical Approval Not applicable.

Consent to Participate All authors consented to participate.

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