

SUBIRRIGATION AS CLIMATE-ADAPTATION TOOL: PROCESS-BASED ASSESSMENT USING FLUSH MODEL IN NORDIC CONDITIONS

L'IRRIGATION SOUTERRAINE COMME OUTIL D'ADAPTATION AU CLIMAT: ÉVALUATION BASÉE SUR LES PROCESSUS À L'AIDE DU MODÈLE FLUSH DANS LES CONDITIONS NORDIQUES

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ABSTRACT

Climate change is intensifying hydroclimatic variability in Nordic regions, with more excess water during snowmelt and heavier rainfall interspersed with dry growing seasons. Conventional subsurface drainage (CV) in northern Finland, designed for rapid dewatering, effectively controls excess water but often exports water that could sustain crops later in the season. Controlled drainage (CD) and controlled drainage with subirrigation (CD-SI) convert drainage networks into active water-regulation systems. By retaining and redistributing water through subsurface drains, they stabilize GW levels, enhance soil moisture buffering, strengthen soil-plant-atmosphere coupling and reduce drainage losses. To quantify these benefits under current and future climates, we extended the two-dimensional FLUSH hydrological model with a new subirrigation routine and simulated CD-SI for a flat field in northern Finland. Forcing data were derived from downscaled, bias-corrected CMIP6 projections from the EC-Earth3 model from Google Earth Engine (SSP-245 and SSP-585) and processed to hourly meteorological inputs. We found that at the end of the century (SSP5-8.5) there will be a wetter growing season, with cumulative precipitation exceeding the historical (450–500 mm) and the drier baseline (400–450 mm). Subirrigation demand will be reduced, with most seasons requiring 20–30 mm additional water. Evapotranspiration rises slightly, while drain discharge becomes more frequent in the late season. Groundwater stays near the surface longer in spring with more variable late-summer declines, especially under SSP5-8.5. These shifts imply that future management should focus less on meeting average supplemental water needs and more on the timing and partitioning of water. Adaptive CD-SI strategies combined with on-field storage can retain spring water, temper peak discharges and buffer late-season shortages. Overall, CD-SI remains a viable adaptation, with the greatest benefits achieved by targeting event-scale variability rather than relying on static seasonal rules.

Keywords: hydroclimatic variability; hydroclimatic variability; meteorological inputs; subsurface drains; Evapotranspiration.

RESUME

Le changement climatique intensifie la variabilité hydroclimatique dans les régions nordiques, avec plus d'eau excédentaire pendant la fonte des neiges et les précipitations plus intenses entrecoupées de saisons de croissance sèches. Le drainage souterrain conventionnel (CV) pratiqué au nord de la Finlande, conçu pour un assèchement rapide, dirige efficacement l'eau excédentaire mais évacue souvent de l'eau qui pourrait nourrir les cultures plus tard dans la saison. Le drainage contrôlé (CD) et le drainage contrôlé avec l'irrigation souterraine (CD-SI) transforment les réseaux de drainage en systèmes actifs de régulation de l'eau. En retenant et en redistribuant l'eau à travers les drains

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souterrains, ils stabilisent les niveaux de la nappe phréatique, rehaussent la capacité tampon de l'humidité du sol, renforcent le couplage sol-plante-atmosphère et réduisent les pertes par drainage. Afin de quantifier ces bénéfices dans le cadre des conditions climatiques actuelles et futures, nous avons étendu le modèle hydrologique bidimensionnel FLUSH avec une nouvelle routine d'irrigation souterraine et simulé le CD-SI sur une parcelle plate au nord de la Finlande. Les données de forçage ont été dérivées des projections CMIP6 à échelle réduite et corrigées des biais issues du modèle EC-Earth3 de Google Earth Engine (SSP-245 et SSP-585), puis traitées pour obtenir des données météorologiques horaires. Nous avons constaté qu'à la fin du siècle (SSP5-8,5), il restera la saison de croissance plus humide, avec des précipitations cumulées dépassant les valeurs historiques (450–500 mm) et le scénario de référence plus sec (400–450 mm).

Les besoins en irrigation souterraine seront réduits, la plupart des saisons ne nécessitant que 20 à 30 mm d'eau supplémentaire. L'évapotranspiration augmentera légèrement, tandis que les écoulements de drainage deviendront plus fréquents à la fin de saison. Au printemps, la nappe phréatique restera plus longtemps proche de la surface, avec des baisses de niveau plus variables à la fin de l'été, en particulier dans le scénario SSP5-8.5. Ces évolutions impliquent que dans l'avenir la gestion devrait moins se concentrer sur la satisfaction des besoins moyens en eau d'appoint et davantage sur le calendrier et la répartition de l'eau. Des stratégies adaptatives de CD-SI combinées à un stockage d'eau sur le terrain permettraient de retenir l'eau au printemps, d'atténuer les débits de pointe et de compenser les déficits hydriques à la fin de saison. Dans l'ensemble, le CD-SI demeure une stratégie d'adaptation viable, dont les avantages les plus importants sont obtenus en ciblant la variabilité à l'échelle des événements plutôt qu'en s'appuyant sur des règles saisonnières statiques.

Mots-clés : Variabilité hydroclimatique; Données météorologiques; Drains souterrains; Evapotranspiration.

INTRODUCTION

Hydroclimatic systems across northern agricultural regions are shifting rapidly as the climate intensifies both surplus water and water scarcity during the growing season. In the Nordic context, earlier and more rapid snowmelt and shifts in precipitation seasonality are increasing the variability of soil water availability (Salla et al., 2022). When evapotranspiration exceeds precipitation in early summer, crops may experience water stress, even on wet and fine-textured soils. These dynamics challenge the conventional subsurface drainage system, which prioritizes rapid removal of surplus water and can export water for later use.

Adaptive drainage management, particularly controlled drainage (CD), has emerged as a strategy to resolve drainage with in-season water needs by restricting outflow to elevate groundwater (GW) depth. CD can help retain moisture in the soil and reduce drainage and nutrient losses (Österholm et al., 2015; Rozemeijer et al., 2016; Youssef et al., 2023). However, under increasingly dry summers, CD alone often cannot maintain optimal GW depths. As soils become dry and the water table falls below the

drain level, the capacity for capillary rise and plant water supply declines (Isomäki et al., 2024; Salo et al., 2021). Subirrigation provided through the controlled drainage network (CD-SI) can address this limitation by reversing the hydraulic gradient to supply water from the control structure into the soil, extending root-zone moisture during water-deficit periods (Helmerts et al., 2022).

Climate change is expected to influence the performance and reliability of CD-SI through multiple pathways. First, shifts in precipitation timing and increased atmospheric demand amplify temporal mismatches between water availability and crop water use. This increases the risk of both surface runoff and subsurface drainage when precipitation falls outside peak demand periods (Iglesias & Garrote, 2015; IPCC, 2021). Second, the reliability of water sources for subirrigation is likely to decline under greater hydrological variability; while competing agricultural demand may limit supplies during low-flow periods (Schewe et al., 2014). Third, soil physical properties—particularly pore-size distribution and hydraulic conductivity—can dominate water distribution under dry and high-evapotranspiration (ET)

conditions (Feddes et al., 1976; Scanlon et al., 2002). Together, these factors imply that the benefits of CD-SI will be highly climate-dependent.

While CD is well-established to reduce drainage and nutrient losses (Österholm et al., 2015; Rozemeijer et al., 2016), there is little practical evidence on when to initiate subirrigation or which hydrologic indicators best signal the need for SI under variable weather and climate. Common triggers based on groundwater depth, drain flow, or control structure levels have not been systematically tested across soils and controlled settings. Field trials, moreover, often miss key subsurface processes such as lateral seepage and preferential flow (Turunen et al., 2015) and system behavior can also vary between dry and wet years (Salo et al., 2021). Thus, the need for simulating the field condition is necessary.

Process-based, field-scale hydrological models offer a transparent framework for testing CD-SI under controlled conditions. Models that resolve variably saturated flow, tile drainage, and groundwater exchange can quantify how control levels and irrigation inputs shape groundwater dynamics and drainage losses across diverse weather conditions (Tähtikarhu et al., 2025). The FLUSH model has been used extensively in Nordic settings to simulate drainage-groundwater interactions and CD behavior (Salo et al., 2021; Warsta et al., 2013).

Although other tools (e.g., HYDRUS) have been applied to controlled drainage (Chrysanthopoulos et al., 2024; Varvaris et al., 2021), subirrigation is often represented only indirectly in many frameworks, limiting their utility for operational decision support (de Wit et al., 2024). Extending FLUSH to simulate reversed flow from drainage networks enables direct evaluation of CD-SI as an integrated management system.

High-resolution meteorological forcing and settings allow FLUSH to resolve event-scale precipitation intensity and diurnal evapotranspiration demand that drive rapid groundwater and drain flow responses in Nordic fields. Sub-daily rainfall variability controls infiltration and surface runoff and its absence can bias drainage losses (IPCC, 2021; Westra et al., 2014). In snow-affected climates, melt often occurs within a short time around daytime peaks, and hourly temperature and radiation are needed to represent melt-refreeze (Hock, 2003).

Drainage models developed for water table management, such as DRAINMOD, have used hourly hydrology to match observed, fast-drain responses and water table fluctuations (Skaggs et al., 2012). Prior CD-SI simulations have frequently relied on daily or coarse sub-daily forcing or on temporally disaggregated series without evaluating how temporal bias propagates to control-level adjustments. This limits transferability under climate change, when short-duration precipitation extremes and intra-day heat stress are projected to intensify (IPCC, 2021). By driving FLUSH with bias-corrected, dynamically downscaled hourly climate series, we reduce temporal aggregation errors (Kavetski et al., 2011) and can explicitly test how event-scale meteorology governs subirrigation need across the considered years.

Here, we studied an extended, two-dimensional version of FLUSH with a new subirrigation routine to examine how climate change modifies the need for and benefits of subirrigation in a flat agricultural field in northern Finland. Using CMIP6-derived, dynamically downscaled and bias-corrected meteorological inputs at hourly resolution, we simulate CD-SI under current conditions and project 21st-century climates (SSP-245 and SSP-585). We aim to: (i) quantify long-term patterns and interannual variability in subirrigation demand under a changing climate; and (ii) evaluate the model's ability to reproduce groundwater depth dynamics and flow behavior relevant to climate-sensitive subirrigation requirements.

STUDY AREA AND EXPERIMENTAL SETUP

The study was implemented at an agricultural field in Sievi, northern Finland (Figure 1a). The field is characterized by flat topography, with a mean slope of less than 0.2%. The total field area is 2.3 ha. The field was subsurface-drained in June 2015 and has been under continuous hydrological monitoring since the installation of the pipe drainage (Salo et al., 2021).

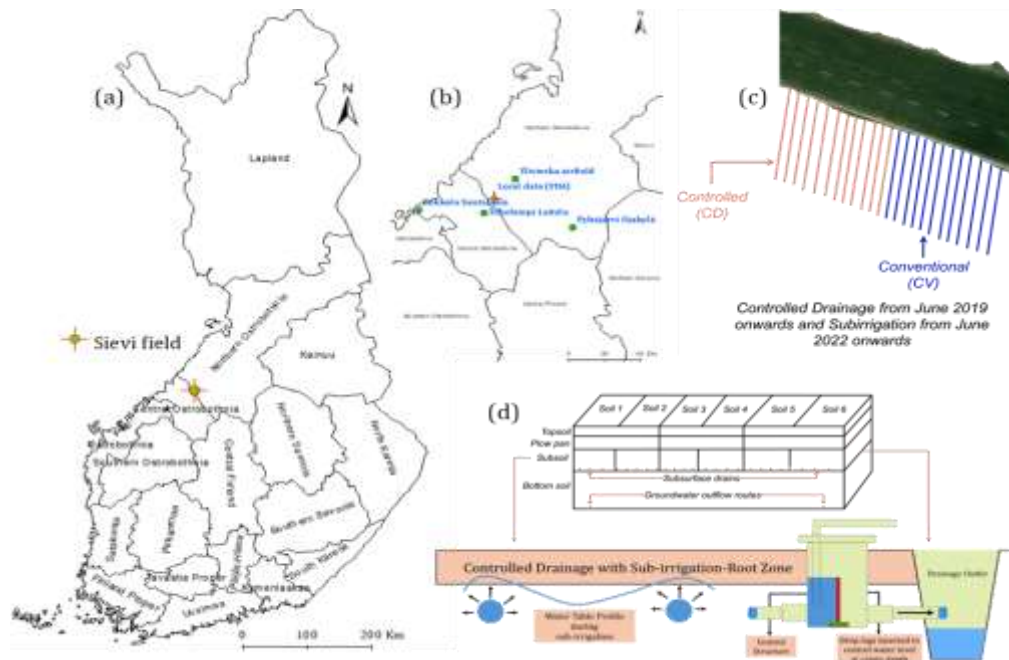


Figure 1. (a) The location of the Sievi field, (b) meteorological observation stations, (c) the field with Conventional (CV), Controlled (CD) and Subirrigation (CD-SI) drainage systems installed and (d) the soil (simulated) profile is divided into six separately parameterized soil sections [modified from (Bhattacharjee et al., 2026)]

Drainage systems in the field

Initially, the field was divided into eight experimental plots, equipped with subsurface drainage. Three subsurface drains were installed per plot with a drain spacing of 15 m and a drain depth of 1 m. In 2019, the experimental setup was modified to study controlled drainage (CD) (Äijö et al., 2023). In 2022, Subirrigation was introduced into those four plots where controlled drainage was installed.

Drainage flows from the controlled and conventional areas were routed to separate collector ditches (Salo et al., 2021). Drain discharge was measured using ultrasonic flow meters, and from summer 2019 onward, discharge measurements were aggregated by CD drainage systems (CD vs. CV in Figure 1d). Additional water (subirrigation) was supplied from the Vääräjoki River and pumped to a distribution well located within the controlled drainage area. Water levels were regulated via a control well that allowed adjustment of the drainage outlet elevation. During the growing seasons in 2019 and 2020, irrigation water was pumped using a combustion engine-driven pump. Subirrigation was applied at the controlled drainage site in June 2022

Groundwater (GW) depth

Groundwater depths were monitored using manual observations conducted approximately twice per week in each of the original eight plots (Figure 1c). Each plot was equipped with seven groundwater observation tubes installed at distances ranging from 0.2 to 7.5 m from the nearest subsurface drain. The tubes were installed to a depth of 2.5 m and perforated over the lower 1.5 m to allow groundwater balance

Soil types

The soil texture varies from loam to loamy sand, with coarser materials dominating in the field (Figure 1d). Soil sampling was conducted in multiple field campaigns. During the 2019 campaign, undisturbed soil cores were collected at three locations from the topsoil (20-25 cm), the plow pan layer (35-40 cm) and at six locations from the subsoil (95-100 cm). Soil hydraulic properties were defined using a

combination of field measurements and literature-based values for structured clay and loamy soils (Salo et al., 2021; Turunen et al., 2013; Warsta et al., 2014). For modeling purposes, the soil profile was divided into four separate layers, each assigned layer-specific hydraulic conductivities to represent both soil matrix and macropore flow domains.

Meteorological Observations

The study area is in a cold-temperate climate zone, characterized by long winter dormancy, spring snowmelt and short growing seasons dominated by summer and early autumn rainfall. Meteorological data, including precipitation, air temperature, relative humidity, wind speed and solar radiation were obtained from the Finnish Meteorological Institute (FMI) for the period 2015-2018 (Figure 1b). This data was used as hourly input for the FLUSH model to represent multiple hydrological years. Based on compiled FMI station data, upward and downward longwave radiation were calculated using the Stefan-Boltzmann law. Potential evapotranspiration (PET) was estimated using the FAO Penman-Monteith equation (Allen et al., 1998) and used as an input for hydrological simulations. This study builds on the earlier FLUSH model applications by Salo et al. (2021) and continuity of drainage scenarios by Bhattacharjee et al. (2026) in Sievi. Additional information on the field conditions and drainage installation can be found in these articles.

METHODS

Figure 2 shows the methodology of this study to simulate the subirrigation at the Sievi field site and related climate projections.

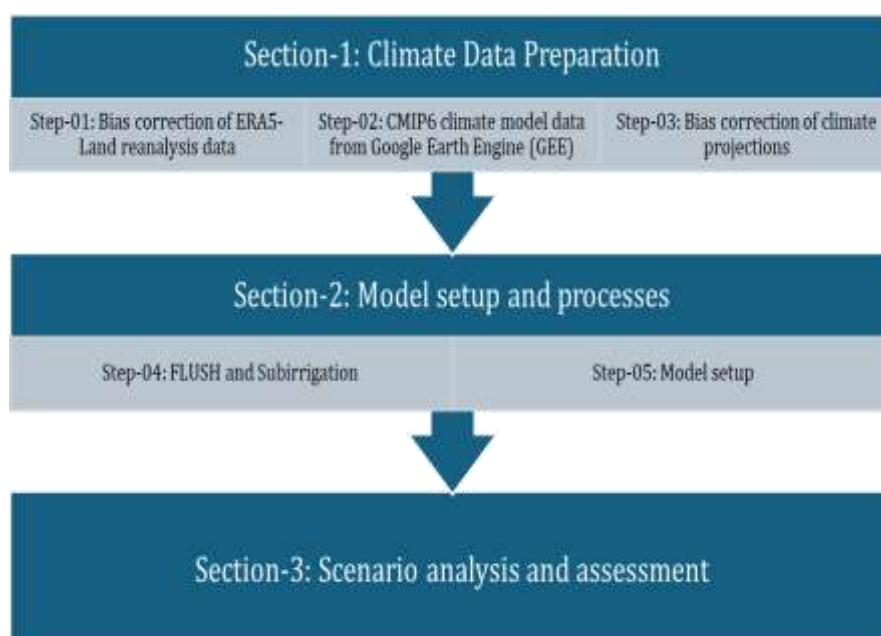


Figure 2. Detailed processes applied in this study

Section-1: Climate data preparation

Step-01: Bias correction of ERA5-Land reanalysis data

The meteorological observations were available from 2015 onwards. Thus, we checked all nearby stations of the Sievi field site (Figure 1) to generate a time series from 2000 to 2014. However, there were many missing values for the mentioned meteorological variables. Thus, the observed reference

climatology for bias correction was derived from the ERA5-Land hourly reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts.

ERA5-Land data covers the period 2000-2008, which was used as the observational baseline. ERA5-Land variables were utilized to have 2 m air temperature, 2 m dew point temperature, total precipitation, 10 m wind components and surface solar radiation downward. ERA5-Land does not provide relative humidity. Therefore, relative humidity was derived from air temperature and dew point temperature using the Magnus equation (Alduchov & Eskridge, 1996).

Step-02: CMIP6 climate model data from Google Earth Engine (GEE)

Future climate projections were obtained from the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) dataset available in the Google Earth Engine (GEE) platform. The dataset provides statistically downscaled Coupled Model Intercomparison Project Phase 6 (CMIP6) simulations at a spatial resolution of approximately 0.25°.

For this study and particular field site, we evaluated EC-Earth3 climate model projections ([GEE script for climate projections](#), available on GEE). Historical (2000-2008), SSP2-4.5 and SSP5-8.5 were used for three different periods of the 21st century. Near-surface air temperature (tas, unit: K), precipitation flux (pr, unit: kgm⁻²s⁻¹), shortwave radiation (rsds, unit: Wm⁻²), near-surface wind speed (SfcWind, unit: ms⁻¹) and relative humidity (hurs, %) were extracted from the GEE for further analysis.

Step-03: Bias correction of climate projections

A monthly delta bias-correction approach was applied to the climate variable. Different correction schemes were used depending on variable characteristics. Temperature and relative humidity were corrected using additive adjustments:

$$X_{corrected} = X_{raw} + (\bar{X}_{ERA5} - \bar{X}_{CMIP6})$$

Where, $X_{corrected}$ is the corrected variable, X_{raw} is the original CMIP6 output, $\bar{X}_{ERA5}$ is the ERA5 monthly climatological mean, and $\bar{X}_{CMIP6}$ is the CMIP6 monthly climatological mean.

Precipitation, wind speed, and solar radiation were corrected using multiplicative scaling factors:

$$X_{corrected} = X_{raw} \times \frac{\bar{X}_{ERA5}}{\bar{X}_{CMIP6}}$$

Precipitation correction factors were limited to 0.1-10, whereas wind speed and solar radiation correction factors were restricted to 0.5-2.0. Minimum denominator thresholds were additionally applied to avoid division by near-zero values. Corrected relative humidity values were clipped to the physically realistic range of 0-100%, while precipitation and wind speed were constrained to non-negative values. Following preprocessing and bias correction, spatial averages were extracted at the study point using the mean reducer function in GEE. To ensure consistency among variables and scenarios, all CMIP6 variables were converted into standardized physical units before analysis.

Section-2: Model Setup and Processes

Step-04: FLUSH and subirrigation

The **FLUSH model** (Warsta et al., 2013) is a three-dimensional (3D), process-based hydrological model specifically developed for **drained agricultural fields under Nordic climatic conditions**. FLUSH couples **two-dimensional (2D) surface flow** with **3D subsurface flow**, providing a physically consistent representation of interactions among precipitation, snowmelt, infiltration, evapotranspiration and artificial drainage. Subsurface flow is simulated using a **dual-permeability approach** (Gerke & van

Genuchten, 1993), in which water moves through both soil matrix and macropore domains. Water flow in both domains is governed by **Richards et al. (1931)**. In this study, we used FLUSH 2D because the regular layout of the drainage system and flat topography allowed neglecting one lateral dimension.

In FLUSH, the soil domain gets water inputs from **precipitation, snowmelt and irrigation through drain pipes**. Water is lost through **evapotranspiration, drain discharge, surface runoff and groundwater outflow**. Drain discharge is calculated separately for the matrix and macropore domains using a **Darcy-based sink term** applied to drainpipe cells. Controlled drainage is represented by a **threshold-based outlet function**, whereby drainage outflow is restricted when the hydraulic head in the drainpipe cell remains below a prescribed control level. The drain discharge flux is calculated as:

$$q_s = \frac{H_c - (H_s + H_{ctrl})}{\Omega_s} A_s K_s$$

where q_s (m³/h) is the drain discharge flux, H_c (m) is the hydraulic head in soil, H_s (m) is the hydraulic head in drainpipe, H_{ctrl} (m) is the control level, Ω_s (m) is the drain entrance resistant, A_s (m²) is the area of drainpipe and K_s (m/h) is the hydraulic conductivity in soil.

Groundwater outflow is simulated as a local sink (Feddes et al., 1976). Snow accumulation, soil freezing and thawing are simulated using the **energy-balance approach** by Koivusalo et al. (2001). Evapotranspiration is partitioned within the soil profile based on root depth. Numerically, FLUSH employs **finite volume discretization**, an **implicit Euler scheme** for time integration and **MPI-based parallelization** (Warsta et al., 2013).

Subirrigation is a new routine in the FLUSH model, used as a head-driven exchange between the drain network and the subsurface domain. Subirrigation inputs water into the matrix and macropore domains and occurs when the groundwater head within a

soil cell with a drain pipe is lower than the control elevation in the drainage system. Subirrigation is activated under the condition:

$$H_c < H_s + H_{ctrl}$$

where the variables are as defined above. When this condition is met, the volumetric subirrigation flux is calculated using q_{sub} (m³/h) as the subirrigation volumetric flux.

Step-05: Model setup

To simulate drainage systems of the Sievi field site along with the climate projections:

- First, the initial model setup by Salo et al. (2021) and the recalibration study by Bhattacharjee et al. (2026) were considered for the initialization of this study. In these studies, a 2D computational grid was parameterized based on the data collected from the field and literature.
- The length and width of each cell in the computational grid were 2 m and the depth of a cell varied from 0.02 to 0.5 m. In total, there were 192 cells in the x-direction, 1 in the y-direction and 32 in the z-direction. The computational domain was 384 m in the x-direction, 2 m in the y-direction and 3.4 m in the z-direction.
- The description and updates of the input parameters are listed in Table 1 (Bhattacharjee et al., 2026). All simulations were executed on the **CSC's Puhti supercomputer**, using **16 parallel subprocesses**.
- From these model results, the existing field condition-based subirrigation and other water balance components were obtained, which were used as a baseline to compare with the climate projections.

- Second, hourly meteorological data of the EC-Earth3 model were prepared to set up each scenario to provide to the FLUSH model. In total, the following scenarios were prepared for the simulation.
 - Historical (2000-2008)
 - For each SSP-245 and SSP-585
- 2020-2035 for the near century (Near-Cent)
- 2045-2064 for the middle of the century (Mid-Cent)
- 2075-2094 at the end of the 21st century (End-Cent)

Section-3: Scenario analysis and assessment

FLUSH produces hourly time series of key hydrological variables, including GW depth, ET, water outflows and soil water storage. To evaluate CD-SI on the field-scale water balance, the climate projection scenarios were simulated. All SSP-based CD-SI scenarios were compared with each other in addition to the historical scenarios.

The results for the growing season periods (May-Sep) were studied to evaluate interannual hydrological variability under varying meteorological conditions. The modeled GW depths were extracted at 28 spatial locations distributed between subsurface drains to capture in-field variability. At each location, GW depths were simulated separately for the soil matrix and macropore domains.

For different steps of this study, many Python scripts were developed to extract and analyze different variables consistently across all the scenarios ([Script for analysis](#), available on GitHub). The scripts were used to: (i) assess the future projection of subirrigation (ii) estimate cumulative water balance components and (iii) evaluate differences in drain discharge and other water balance components.

RESULTS

Water Balance

Across the growing season, Figure 3 shows wetter futures than the historical period. Cumulative precipitation increases at the end of the century (SSP5-8.5) against 450-500 mm historical, whereas the grey baseline is drier (400-450 mm). Subirrigation demand becomes less negative compared to much larger supplemental needs under the baseline (55-60 mm). Evapotranspiration increases to nearly 200-230 mm historically and around 220-260 mm in the future. Drain discharge rises to 40-60 mm (SSP2-4.5) and 55-75 mm at the end of the century (SSP5-8.5). Surface runoff remains small early but also indicates more stormflow later in the century. Groundwater flow increases steadily and is lower than the baseline (75-85 mm).



Figure 3. Growing-season (May-Sep) cumulative water balance of different components for each scenario relative to the 1st of May. Each scenario represents an ensemble average with a shading of the 10th-90th percentile and the ERA5 baseline

Subirrigation

Figure 4a summarizes seasonal subirrigation demand, with most seasons requiring approximately 20-30 mm and occasional years showing substantially higher needs. Central tendencies are broadly similar between the historical and future periods. In Figure 4b, linear trend lines within each time window are nearly flat with no consistent change in demand over time. Figure 4c also supports the limited change in typical seasonal demand under the future climate. However, it shows substantial variability from year to year.

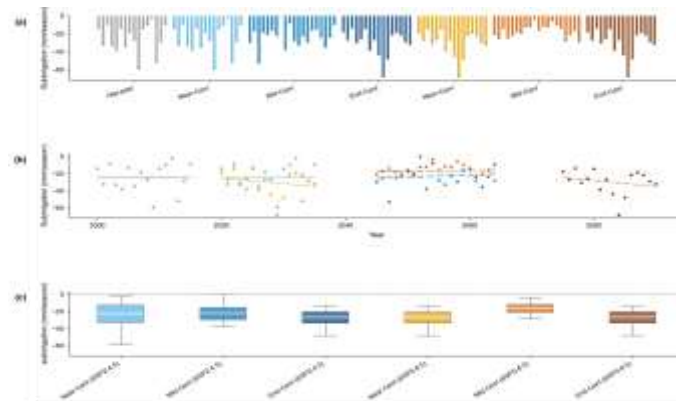


Figure 4. Subirrigation demand across scenario periods (a) Annual totals; error bars: p10-p90 spread. (b) linear trends of periods (c) Seasonal anomalies against historical mean based on Mann-Whitney U significance (* $p<0.05$, ** $p<0.01$, *** $p<0.001$).

Changes in different components

Across variables, future seasons look broadly similar to the historical distribution. Evapotranspiration medians under both SSP2-4.5 and SSP5-8.5 are slightly higher than historical (Figure 5a), but differences among future windows are not statistically significant (n.s.). Drain discharge shows more frequent high-flow seasons under SSP5-8.5, though most differences remain within historical variability and are largely non-significant. Groundwater flow changes are small across scenarios. Overall, Figure 5 indicates slight increases in ET, but not statistically significant changes compared to the historical distributions.

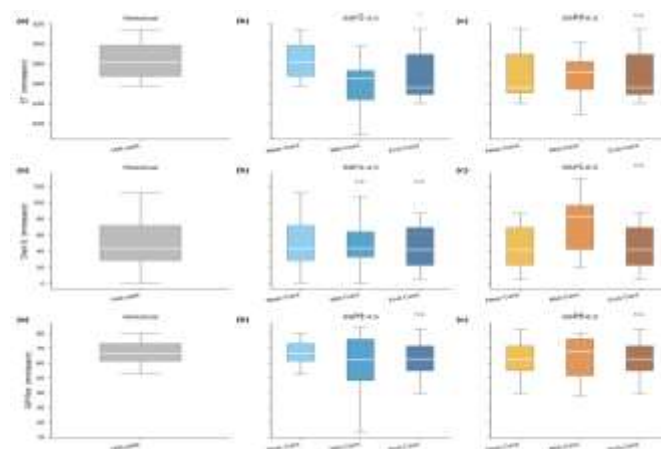


Figure 5. Growing-season ET, Drian Q, and GW flow distributions with Mann-Whitney U vs. historical period (* $p<0.05$, ** $p<0.01$, *** $p<0.001$).

GW depth

Historically, the water table rises near the surface in May-June and goes back to around 1-2 m through July-September (Figure 6). Under SSP2-4.5, near-surface conditions continue longer into early summer and interannual spread increases during late-season drawdown. These changes are amplified under SSP5-8.5, particularly by the end of the century, where shallow conditions are most constant and late-summer declines become more evident. Overall, projections point to longer periods of saturated or near-saturated soils in spring and late-summer declines, especially under SSP5-8.5.

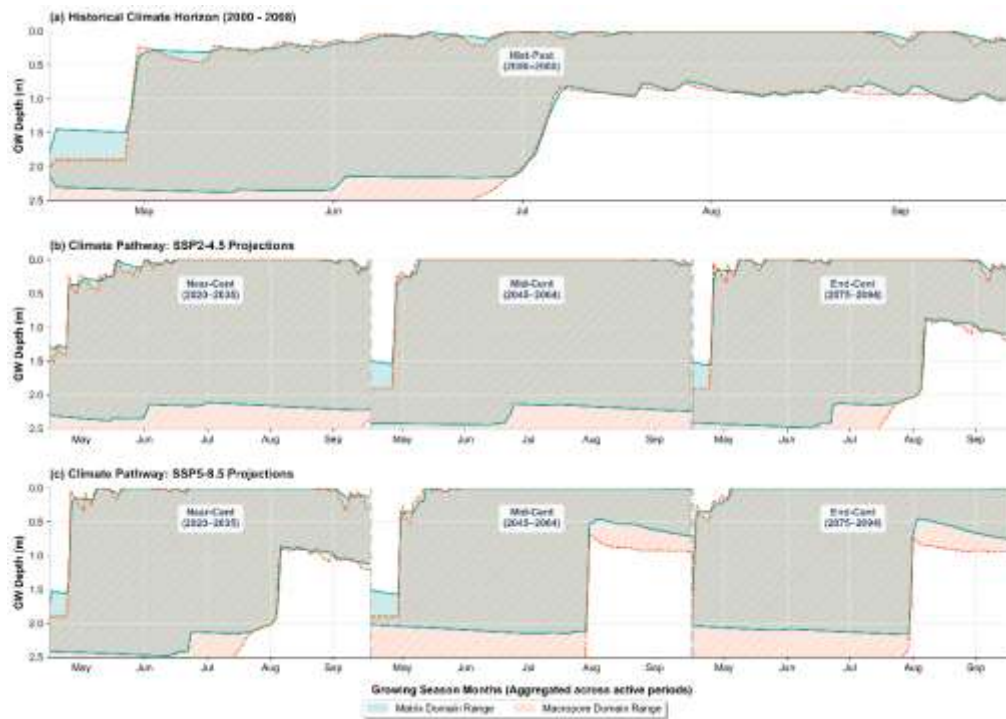


Figure 6. GW depth variations across the scenario periods

DISCUSSION

Our results indicate a modest but reasonable shift toward more wet growing seasons under future climates. Especially, with the strongest signal by the end of the century under SSP5-8.5. Cumulative precipitation increases relative to the historical period and the baseline. Subirrigation demand becomes less negative, which means smaller supplemental need in near and far futures. Collectively, these responses are consistent with projections of intensified precipitation in a warming climate with greater moisture-holding capacity and modest increases in evaporative demand, particularly later in the season (Allan et al., 2020; IPCC, 2021; Trenberth, 2011). The widening uncertainty bands late in the season and under higher emissions represent the spread in regional precipitation projections reported by the CMIP6 ensemble (IPCC, 2021).

The hydrologic partitioning diagnosed in this study aligns with the process expectations. First, more frequent precipitation during the growing season supports slightly higher ET but does not produce statistically significant results from historical distributions. This may happen because plant-physiological and energy controls ET increases even when the atmospheric demand rises (Novick et al., 2016; Williams et al., 2019). Second, larger increases appear in drainage and occasional runoff, particularly under SSP5-8.5. That means additional water is increasingly routed through rapid flow paths, which are consistent with observed and modeled behavior in tile-drained landscapes (King et al., 2015). Third, groundwater outflow changes are small relative to interannual variability. However, GW-depth shows

longer periods of near-surface saturation in spring and more variable late-summer declines, especially at the end of the century SSP5-8.5. This pattern may happen with more wet springs followed by higher atmospheric demand and variable summer season (IPCC, 2021; Milly et al., 2008).

The hydroclimatic signals are strongest late in the season under SSP5-8.5, but many median changes remain within historical variability, and several inter-period differences are not statistically significant. These outcomes reflect known model spread in regional warm-season precipitation and convective processes (IPCC, 2021). Our results also depend on the representation of soil hydraulic properties, macropore flow and drainage control logic. Errors in these components can bias the partitioning of excess water among ET, discharge, runoff and groundwater declines (Beven & Germann, 2013). Although our analysis aggregates across growing seasons, crop choice, planting date, and management can shift ET and drainage timing relative to climate forcing (Mueller et al., 2016).

As a future part of this study, we are planning to (i) evaluate event-scale responses to better resolve the projected increase in late-season runoff and drain flow and (ii) test adaptive drainage-water management strategies. Multi-model hydrologic ensembles and storylines that sample different storm series would help us better to understand the risk beyond the ensemble mean (Shepherd et al., 2018).

CONCLUSIONS

Using an hourly process-based climate simulation in FLUSH with subirrigation, we show that growing seasons in a Nordic agricultural field are likely to become wetter under SSP5-8.5 at the end of the century. Additional precipitation translates into non-significant increases in evapotranspiration but a marked reduction in subirrigation demand. Groundwater remains nearer to the surface for longer in spring and declines more variably during late summer. These shifts imply that future management should focus less on meeting average supplemental water needs and more on the timing and partitioning of water. Adaptive CD-SI strategies combined with on-field storage can retain spring water, moderate peak discharges and buffer late-season shortages. Overall, CD-SI remains a viable adaptation, with the greatest benefits achieved by targeting event-scale variability rather than relying on static seasonal rules.

REFERENCES

- Äijö, H., Myllys, M., Salo, H., Salla, A., Paasonen-Kivekäs, M., Koivusalo, H., Mäkelä, M., Nurminen, J., Paavonen, E., Isomäki, K., Jokinen, V., Laine-Kaulio, H., Häggblom, O., & Sikkilä, M. (2023). Vesitalouden hallinta vesiensuojelussa 2 (VesiHave 2) Loppuraportti 2023 [Water Management in Water Protection (VesiHave 2) - Final Report 2023].
- Alduchov, O. A., & Eskridge, R. E. (1996). Improved Magnus form approximation of saturation vapor pressure. *Journal of Applied Meteorology* (1988-2005), 601-609.
- Allan, R. P., Barlow, M., Byrne, M. P., Cherchi, A., Douville, H., Fowler, H. J., Gan, T. Y., Pendergrass, A. G., Rosenfeld, D., Swann, A. L. S., Wilcox, L. J., & Zolina, O. (2020). Advances in understanding large-scale responses of the water cycle to climate change. *Annals of the New York Academy of Sciences*, 1472(1), 49-75. <https://doi.org/10.1111/NYAS.14337>
- Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56.
- Beven, K., & Germann, P. (2013). Macropores and water flow in soils revisited. *Water Resources Research*, 49(6), 3071–3092. <https://doi.org/10.1002/wrcr.20156>
- Bhattacharjee, J., Salo, H., Mäkelä, M., & Koivusalo, H. (2026). Integrating Controlled Drainage and Subirrigation Demand: Insights from FLUSH Simulations in a Nordic Agricultural Field [Manuscript submitted for publication]. *Journal of Hydrology*.
- Chrysanthopoulos, E., Perdikaki, M., Markantonis, K., & Kallioras, A. (2024). Integrated Subsurface Hydrologic Modeling for Agricultural Management Using HYDRUS and UZF Package Coupled with MODFLOW. *Water*, 16(22), 3297. <https://doi.org/10.3390/W16223297>
- de Wit, J. A., van Huijgevoort, M. H. J., van Dam, J. C., van den Eertwegh, G. A. P. H., van Deijl, D., Ritsema, C. J., & Bartholomeus, R. P. (2024). Hydrological consequences of controlled drainage with subirrigation. *Journal of Hydrology*, 628, 130432. <https://doi.org/10.1016/J.JHYDROL.2023.130432>

- Feddes, R. A., Kowalik, P., Kolinska-Malinka, K., & Zaradny, H. (1976). Simulation of field water uptake by plants using a soil water dependent root extraction function. *Journal of Hydrology*, 31(1–2), 13–26. [https://doi.org/10.1016/0022-1694\(76\)90017-2](https://doi.org/10.1016/0022-1694(76)90017-2)
- Gerke, H. H., & van Genuchten, M. T. (1993). A dual-porosity model for simulating the preferential movement of water and solutes in structured porous media. *Water Resources Research*, 29(2), 305–319. <https://doi.org/10.1029/92WR02339>
- Helmerts, M. J., Abendroth, L., Reinhart, B., Chighladze, G., Pease, L., Bowling, L., Youssef, M., Ghane, E., Ahiablame, L., Brown, L., Fausey, N., Frankenberger, J., Jaynes, D., King, K., Kladienko, E., Nelson, K., & Strock, J. (2022). Impact of controlled drainage on subsurface drain flow and nitrate load: A synthesis of studies across the U.S. Midwest and Southeast. *Agricultural Water Management*, 259, 107265. <https://doi.org/10.1016/J.AGWAT.2021.107265>
- Hock, R. (2003). Temperature index melt modelling in mountain areas. *Journal of Hydrology*, 282(1–4), 104–115. [https://doi.org/10.1016/S0022-1694\(03\)00257-9](https://doi.org/10.1016/S0022-1694(03)00257-9)
- Iglesias, A., & Garrote, L. (2015). Adaptation strategies for agricultural water management under climate change in Europe. *Agricultural Water Management*, 155(2), 113–124. <https://doi.org/10.1016/j.agwat.2015.03.014>
- IPCC. (2021). *Climate Change 2021 – The Physical Science Basis*. Climate Change 2021 – The Physical Science Basis. <https://doi.org/10.1017/9781009157896>
- Isomäki, K., Salla, A., Salo, H., & Koivusalo, H. (2024). Hydrological effects of open ditch damming and controlled subsurface drainage in a Nordic agricultural field. *Hydrology Research*, 55(2), 112–127. <https://doi.org/10.2166/nh.2024.053>
- Kavetski, D., Fenicia, F., & Clark, M. P. (2011). Impact of temporal data resolution on parameter inference and model identification in conceptual hydrological modeling: Insights from an experimental catchment. *Water Resources Research*, 47(5), 5501. <https://doi.org/10.1029/2010WR009525>
- King, K. W., Williams, M. R., & Fausey, N. R. (2015). Contributions of Systematic Tile Drainage to Watershed-Scale Phosphorus Transport. *Journal of Environmental Quality*, 44(2), 486–494. <https://doi.org/10.2134/JEQ2014.04.0149>
- Koivusalo, H., Heikinheimo, M., & Karvonen, T. (2001). Test of a simple two-layer parameterisation to simulate the energy balance and temperature of a snow pack. *Theoretical and Applied Climatology*, 70(1–4), 65–79. <https://doi.org/10.1007/s007040170006>
- Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. (2008). Stationarity is dead: Whither water management? *Science*, 319(5863), 573–574. <https://doi.org/10.1126/SCIENCE.1151915>
- Mueller, N. D., Butler, E. E., McKinnon, K. A., Rhines, A., Tingley, M., Holbrook, N. M., & Huybers, P. (2016). Cooling of US Midwest summer temperature extremes from cropland intensification. *Nature Climate Change*, 6(3), 317–322. <https://doi.org/10.1038/nclimate2825>
- Novick, K. A., Ficklin, D. L., Stoy, P. C., Williams, C. A., Bohrer, G., Oishi, A. C., Papuga, S. A., Blanken, P. D., Noormets, A., Sulman, B. N., Scott, R. L., Wang, L., & Phillips, R. P. (2016). The increasing importance of atmospheric demand for ecosystem water and carbon fluxes. *Nature Climate Change* 6:11, 6(11), 1023–1027. <https://doi.org/10.1038/nclimate3114>
- Österholm, P., Åström, M., & Yli-Halla, M. (2015). Controlled drainage as a tool for minimizing environmental impacts from acid sulfate soils in Finland. *Environmental Earth Sciences*, 73(7), 3457–3470. <https://doi.org/10.1007/s12665-014-3649-0>
- Richards, L. A., Chem Phys, J., & A Richards, B. L. (1931). Capillary Conduction of Liquids through Porous Mediums. *Physics*, 1(5), 318–333. <https://doi.org/10.1063/1.1745010>
- Rozemeijer, J. C., Visser, A., Borren, W., Winegram, M., Van Der Velde, Y., Klein, J., & Broers, H. P. (2016). High-frequency monitoring of water fluxes and nutrient loads to assess the effects of controlled drainage on water storage and nutrient transport. *Hydrology and Earth System Sciences*, 20(1), 347–358. <https://doi.org/10.5194/HESS-20-347-2016>
- Salo, H., Salla, A., & Koivusalo, H. (2021). Seasonal effects of controlled drainage on field water balance and groundwater levels. *Hydrology Research*, 52(6), 1633–1647. <https://doi.org/10.2166/NH.2021.056>
- Scanlon, B. R., Healy, R. W., & Cook, P. G. (2002). Choosing appropriate techniques for quantifying groundwater recharge. *Hydrogeology Journal*, 10(1), 18–39. <https://doi.org/10.1007/S10040-001-0176-2>
- Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N. W., Clark, D. B., Dankers, R., Eisner, S., Fekete, B. M., Colón-González, F. J., Gosling, S. N., Kim, H., Liu, X., Masaki, Y., Portmann, F. T., Satoh, Y., Stacke, T., Tang, Q., Wada, Y., ... Kabat, P. (2014). Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences*, 111(9), 3245–3250. <https://doi.org/10.1073/PNAS.1222460110>

- Shepherd, T. G., Boyd, E., Calel, R. A., Chapman, S. C., Dessai, S., Dima-West, I. M., Fowler, H. J., James, R., Maraun, D., Martius, O., Senior, C. A., Sobel, A. H., Stainforth, D. A., Tett, S. F. B., Trenberth, K. E., van den Hurk, B. J. J. M., Watkins, N. W., Wilby, R. L., & Zenghelis, D. A. (2018). Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. *Climatic Change* 2018 151:3, 151(3), 555–571. <https://doi.org/10.1007/S10584-018-2317-9>
- Skaggs, R. W., Youssef, M. A., & Chescheir, G. M. (2012). DRAINMOD: Model Use, Calibration, and Validation. *Transactions of the ASABE*, 55(4), 1509–1522. <https://doi.org/10.13031/2013.42259>
- Tähtikarhu, M., Räsänen, T. A., Hyväluoma, J., Piayda, A., & Myllys, M. (2025). Analysing hydrological impacts of controlled drainage, peat thickness and groundwater fluxes in cultivated peat soils. *Acta Agriculturae Scandinavica Section B: Soil and Plant Science*, 75(1). <https://doi.org/10.1080/09064710.2025.2454388>
- Trenberth, K. E. (2011). Changes in precipitation with climate change. *CLIMATE RESEARCH*, 47, 123–138. <https://doi.org/10.3354/cr00953>
- Turunen, M., Warsta, L., Paasonen-Kivekäs, M., Nurminen, J., Alakukku, L., Myllys, M., & Koivusalo, H. (2015). Effects of terrain slope on long-term and seasonal water balances in clayey, subsurface drained agricultural fields in high latitude conditions. *Agricultural Water Management*, 150(3), 139–151. <https://doi.org/10.1016/j.agwat.2014.12.008>
- Turunen, M., Warsta, L., Paasonen-Kivekäs, M., Nurminen, J., Myllys, M., Alakukku, L., Äijö, H., Puustinen, M., & Koivusalo, H. (2013). Modeling water balance and effects of different subsurface drainage methods on water outflow components in a clayey agricultural field in boreal conditions. *Agricultural Water Management*, 121(2), 135–148. <https://doi.org/10.1016/j.agwat.2013.01.012>
- Varvaris, I., Pittaki-Chrysodonta, Z., Duus Børgesen, C., & Iversen, B. V. (2021). Parameterization of two-dimensional approaches in HYDRUS-2D: Part 1. Simulating water flow dynamics at the field scale. *Soil Science Society of America Journal*, 85(5), 1578–1599. <https://doi.org/10.1002/SAJ2.20307>
- Warsta, L., Karvonen, T., Koivusalo, H., Paasonen-Kivekäs, M., & Taskinen, A. (2013). Simulation of water balance in a clayey, subsurface drained agricultural field with three-dimensional FLUSH model. *Journal of Hydrology*, 476, 395–409. <https://doi.org/10.1016/j.jhydrol.2012.10.053>
- Warsta, L., Taskinen, A., Paasonen-Kivekäs, M., Karvonen, T., & Koivusalo, H. (2014). Spatially distributed simulation of water balance and sediment transport in an agricultural field. *Soil and Tillage Research*, 143(SUPPL. 2), 26–37. <https://doi.org/10.1016/j.still.2014.05.008>
- Westra, S., Fowler, H. J., Evans, J. P., Alexander, L. V., Berg, P., Johnson, F., Kendon, E. J., Lenderink, G., & Roberts, N. M. (2014). Future changes to the intensity and frequency of short-duration extreme rainfall. *Reviews of Geophysics*, 52(3), 522–555. <https://doi.org/10.1002/2014RG000464>
- Williams, A. P., Abatzoglou, J. T., Gershunov, A., Guzman-Morales, J., Bishop, D. A., Balch, J. K., & Lettenmaier, D. P. (2019). Observed Impacts of Anthropogenic Climate Change on Wildfire in California. *Earth's Future*, 7(8), 892–910. <https://doi.org/10.1029/2019EF001210>