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Water partitioning in agricultural catchments amidst climate and land use changes in Sweden

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Water balance in agricultural catchments amidst climate and land use changes in Sweden

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Abstract

Crop production depends on water availability from precipitation and soil infiltration and storage. Historically, efforts to enhance soil moisture have focused on modifying agricultural landscapes and hydrological pathways. With climate change increasing water saturation and deficit risks, understanding the role of water diversion and storage in sustaining yields is crucial. This thesis explored how the water balance in agricultural landscapes can be affected by climate change, historical, current and potential future agricultural water management and anthropogenic interventions. Using the Soil and Water Assessment Tool (SWAT+), hydrological modeling was conducted in four Swedish agricultural catchments with varying temperature and precipitation regimes to assess historical and future water balance In **Paper I**, new datasets were developed for soil water, stream networks, open ditches and subsurface drainage. The results showed increased infiltration and water-holding capacity with the soil texture classification system used. Furthermore, the flow path length increased by 14% to 21 %, and two new maps over subsurface drainage were presented. In **Paper II**, modelling water balance in historic and current climate, land use, varying hydromorphology and water storage, resulted in marginal shifts in water partitioning, despite significant increase in subsurface and surface drainage and reduced wetland area over time. In **Paper III**, exploring effect on soil moisture and evapotranspiration under current and future climate in four contracting agricultural catchments showed increased drying of both soil moisture and evapotranspiration with increased warming. Hence partially opposing previous findings. In conclusion, representing historical landscape water balance across scales remains challenging due to variations in data resolution. Historical structures and stream delineation offer insights for enhancing catchment storage and infiltration capacity. However, **Paper I** highlights the necessity of high-resolution data for accurate landscape representation. Future climate change is expected to increase soil moisture drying, but responses at the catchment scale remain ambiguous, necessitating further investigation into soil moisture dynamics under climate impacts.

Keywords: soil moisture, agrometeorology, flood, waterlogging, drought, anthropogenic landscape alteration, climate adaptation

Vattenbalans i jordbruksdominerade avrinningsområden under inverkan av förändrad markanvändning och klimat i Sverige

Abstract

Produktionen av grödor beror på vattentillgången från nederbörd och markinfiltration och lagring. Historiskt har ansträngningar för att förbättra markfuktigheten fokuserat på att modifiera jordbrukslandskap och hydrologiska flödesvägar. Klimatförändringarna ökar riskerna för vattenmättnad och vattenunderskott. Därav är det avgörande att förstå vilken roll vattenavledning och vattenlagring har i jordbrukslandskap för att upprätthålla skördar. Denna avhandling undersökte hur vattenbalansen i jordbrukslandskap kan påverkas av klimatförändringar samt historisk, nuvarande och potentiell framtida förvaltning av jordbruksvatten och antropogena ingrepp. Med hjälp av den hydrologiska modellen Soil and Water Assessment Tool (SWAT+) genomfördes hydrologisk modellering i fyra svenska jordbruksavrinningsområden inom varierande temperatur- och nederbördsregimer för att bedöma historisk och framtida vattenbalans. I **Paper I** utvecklades nya dataset för markfysikaliska parametrar, vattendrag, öppna diken och täckdikning. Resultaten visade på ökad infiltrations- och vattenhållande förmåga beroende på vilket system som användes för texturklassificering. Vidare ökade den sammanslagna längden av vattendrag med 14 % till 21 %. Därtill presenterades två nya kartor över täckdikning. I **Paper II** resulterade modellering av vattenbalansen under historiskt och nuvarande klimat, markanvändning, varierande vattendrag i marginella förändringar av vattenallokering i vattenbalansen, trots betydande ökning av täckdikning, täckning av vattendrag och minskad våtmarksarea över tid. I **Paper III** visade resultaten under nuvarande och framtida klimat från fyra differentierade jordbruksdominerade avrinningsområden en ökad uttorkning av både markfuktighet och evapotranspiration med ökad uppvärmning Sammanfattningsvis är det utmanande att representera historiska landskap på grund av variationer i dataupplösning. Historiska strukturer och vattendrag ger insikter för att förbättra vattenlagring och infiltrationskapacitet. *Nyckelord*: markfuktighet, agrometeorologi, översvämning, vattenmättnad, torka, antropogen landskapsförändring, klimatanpassning

Dedication

Till minne av min mormor och morfar, Elly och Nils Andersson
och farmor och farfar, Gun och Erik Malmquist

"Det är förutan bedrägeri visst och sant,
Att när svalorne flyga på vatten,
Med sina vingar däruti slå,
Ett stort regn vi visserligt få."

- Den Svenska bondepraktikan, 2a upplagan, 1997, Klassikerförlaget

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List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. **Malmquist, L**. & Barron, J. (2023) Improving spatial resolution in soil and drainage data to combine natural and anthropogenic water functions at catchment scale in agricultural landscapes, *Agricultural Water Management*, Volume 283, 108304, ISSN 0378-3774, https://doi.org/10.1016/j.agwat.2023.108304)

II. **Malmquist, L**. & Barron, J. (2024) Effects of nature-based and engineered water infrastructure development on water balance in agricultural landscapes – a historical example from temperate Sweden, (*Manuscript*)

III. **Malmquist, L**., Bieroza, M., Jaramillo, F. & Barron, J. Soil moisture and evapotranspiration response to extreme weather events in four agricultural catchments (*Manuscript*)

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The contribution of Louise Malmquist to the papers included in this thesis was as follows:

I. Analysed and prepared data from national databases, developed the method of extracting subsurface drainage from the economic map, analysed out data, and wrote the manuscript with the support of the co-author.

II. Planned the study together with the co-author, analysed and prepared indata from national databases, ran the hydrological model, analysed out data, and wrote the manuscript with support from the co-author.

III. Planned the study together with the co-authors, collected data from national databases, prepared data to the format of the hydrological model and the weather generator, ran the weather model and model, analysed the climate and hydrological out data, and wrote the manuscript with support from the co-authors.

Additional papers

During the work on this thesis, Louise Malmquist made contributions to the following papers (**I** to **III**) and dataset (**IV**) not included in the thesis:

I. Malmquist, L & Barron, J (2024) *Högfrekvent vattenföringsmätning i Braån, Loftaån, Örsundaån och Ösan år 2022 till 2023*, Uppsala: Institutionen för mark och miljö, URI: https://doi.org/10.54612/a.103r5g5o99

II. Malmquist, L. & Barron, J. (2022) *Identification and synthesis of agrometeorological extreme weather indicators for the temperate-boreal zone.* URI: https://res.slu.se/id/publ/116370

III. Malmquist, L (2021) *Karaktäristik över pilotområden inom projektet Lokalt engagemang för vatten (LEVA) – Första cykeln 2018-2021*, Uppsala: Institutionen för mark och miljö, URI: https://res.slu.se/id/publ/111934

IV. Malmquist, L. *A 50 m spatial representation of probable subsurface drained arable land in central to southern Sweden* (*draft*)

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1. Introduction

Water is a key component in food production and food security. Approximately 78 % of the global cultivated area in 2018 was rainfed, sustaining 60 % of food production. At the same time, agriculture (mainly irrigated) is responsible for an estimated 70 % of total global water withdrawals. This water is used to produce the remaining 40 % of global food[i] (FAO 2021, 2022). In rainfed agricultural systems, two fundamental production factors are the basis for production and productivity: I) the amount and distribution of rainfall and II) the soils' capacity to facilitate infiltration and retain available rainfall. In addition to rainfall and water stored in soils, irrigated agriculture also relies on locally available water storage.

Water availability from precipitation and stored surface and groundwater is being challenged by climate change. Crop production is susceptible to weather extremes including water scarcity, excessive water, and lower and upper temperature boundaries (Hatfield, 2015; Li et al., 2019). The year 2024 was the warmest both globally (WMO, 2025) and in Europe (Copernicus Climate Change Service, 2025) since climate records began. Observed climate trends encompass rising temperatures, increased frequency and duration of warm spells, as well as the magnitude and occurrence of precipitation events, along with higher occurrence of soil moisture droughts (Seneviratne et al., 2021). Higher temperatures increase the likelihood of wet and dry events by increasing the water-holding capacity in the atmosphere and the evaporative demand, though with regional and seasonal variations (Douville et al., 2021). This spatio-temporal variability is expected to increase with every degree of increase in global average temperature (Seneviratne et al., 2021), increasing the risks of scarcity or excess water for agricultural production (Heino et al., 2023; Han et al., 2024).

The mean temperature in Europe, especially in the Nordic region, is increasing twice as fast as the global mean temperature (WMO, 2023, Rantanen et al., 2022). It has been suggested that conditions in the Nordic countries and the temperate-boreal zone have become better suited for crop production due to increased temperatures. This can potentially be favourable,

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[i] Disregarding freshwater and marine food sources

enabling an increased number of harvests and the introduction of new crops and new sowing patterns (Wiréhn, 2018). Indeed, the agro-ecological zones have already shifted northwards (King et al. 2018; Ceglar et al. 2019). However, decreases in the yield of e.g. cereal crops due to droughts have intensified by -3 % per year since 1964 and decreases in cereal yields due to heatwaves and droughts tripled from 1964-1990 to 1991-2015 (Brás et al., 2021). Globally, the importance of water scarcity and excess water is reflected in the share of production losses in the agricultural sector caused by drought and floods. For example, ~65 % of production losses due to drought occurred in the agricultural sector, with almost 20 % production losses per drought event. In comparison, agricultural losses correspond to ~21 % of total production losses to floods, with ~16 % production loss in the agricultural sector per flood event (Fig. 17, FAO, 2023). Water yield gaps (the difference between potential yield or water-limited yield, i.e. yield without the influence of abiotic and biotic stressors, and the actual yield achieved) in northern and central Europe have been estimated to be < 50 % (Schils et al., 2018). This is on the lower side compared to Eastern and Southern Europe (Schils et al., 2018). Nevertheless, the negative effects of extreme weather events on crop yield in recent years also affect the northern high-producing regions, revealing an apparent vulnerability to crop yield in this region (Beillouin et al., 2020).

Soils constitute the largest buffer and filter for water in the landscape and, therefore, largely govern hydrological partitioning and storage of water. Hence, the physical properties of soils can significantly influence water partitioning and storage, as well as crop (or any biomass) production, with explicit importance for rainfed crop production (Falkenmark and Rockström, 2006; Rockström et al., 2009). For centuries, efforts have been made to enhance water availability and soil moisture conditions by altering terrestrial landscapes and modifying hydrological pathways and storages. The aim has been to improve cropping conditions and increase food production and other biomass (Stoate et al., 2009; Ellis et al., 2021). Anthropogenic interventions, leading to drainage, water abstraction and re-diversion of water sources, have an important impact on the global water cycle. Landscapes have been altered by shifts in vegetation, drainage of land and water bodies and water abstraction, reallocation of streams, damming and reshaping of streams (Grill et al., 2019; Belletti et al., 2020; Valipour et al., 2020; Ellis et al., 2021; Fluet-Chouinard et al., 2023). Nevertheless, the anthropogenic influence has only been included in depictions of the hydrological cycle in recent years (e.g. Abbott et al., 2019a).

Agricultural water and soil interventions for mitigation and adaptation aimed at addressing heightened risks of water saturation and water deficits are likely to intensify due to the increasing frequency and intensity of extreme weather events and the extraction of water from available water sources to meet agricultural water needs. Enhancing the capacity for mitigation and adaptation strength in response to water fluctuations throughout agricultural catchments involves improving both increased infiltration for improved storage and drainage, as well as the buffering capacity to retain and release water in a controlled manner at catchment scale. Furthermore, mitigation and adaptation include diverting excess water to alternative areas where damages are less problematic. It is recognised that adaptation and mitigation measures will necessitate local solutions, including both nature-based and engineered approaches as well as combinations of the two concepts (Hewett et al., 2020).

Agriculture in Scandinavia makes up a relatively small proportion of global food production. For instance, cereal production contributes to 0.7 % of global cereal production (FAO, 2024). The agricultural land in Sweden amounts to approximately 7 % of the country's total land area (Statistics Sweden, 2022a), and most of the crop cultivation area is rainfed. Of all fresh water use in Sweden, a minor 3 % is extracted for irrigation (Statistics Sweden, 2022b). Given the increased temperatures and changes in precipitation patterns and amounts, Sweden will face water supply challenges in sustaining rainfed food production and in fulfilling the objectives of the Swedish national food strategy to strengthen and increase national food production (Näringsdepartementet, 2019, 2017; Regeringens proposition 2016/17:104, 2016). There is a need to address of the needs and options for agriculture to adapt and the potential implications of water abstraction, diversion, and storage to ensure long-term resilience to water-related disturbances and sufficient water availability in the cropping systems. Due to the hydrological connectivity of water in the landscape, neither the impact of extreme events on water resources and water availability for crop production, nor the effects of mitigation measures towards extreme events are limited to the individual farm boundary. Therefore, efforts to enhance buffering capacities towards too much or too little water conditions in crop production must be explored, in relation to water demand from other ecosystems and sectors within a given catchment. Hence, there is also a call to explore water allocation and management at a larger scale (Noreen et al., 2017; Bölenius et al., 2020).

2. Aims and research questions

The aim of this thesis was to assess agricultural production and agro-hydrological challenges in Sweden under current and future climate with more frequent and severe weather extremes. This thesis search to answer the question of how the water balance in agricultural landscapes can be affected by climate change and agricultural water management interventions.

To answer this overarching question, the following questions were explored in the respective papers included in this thesis:

I. Does high-resolution spatial data improve our understanding of water flow pathways, water storage and retention potential modified through agricultural water management interventions? (**Paper I**)

II. How does historical and current water retention measures and stream network modifications affect agricultural landscape water balance? **Paper II**)

III. How does current and future extreme weather impact soil moisture availability in agricultural catchments? (**Paper III**)

The scope of this thesis is visualized in Figure 1.

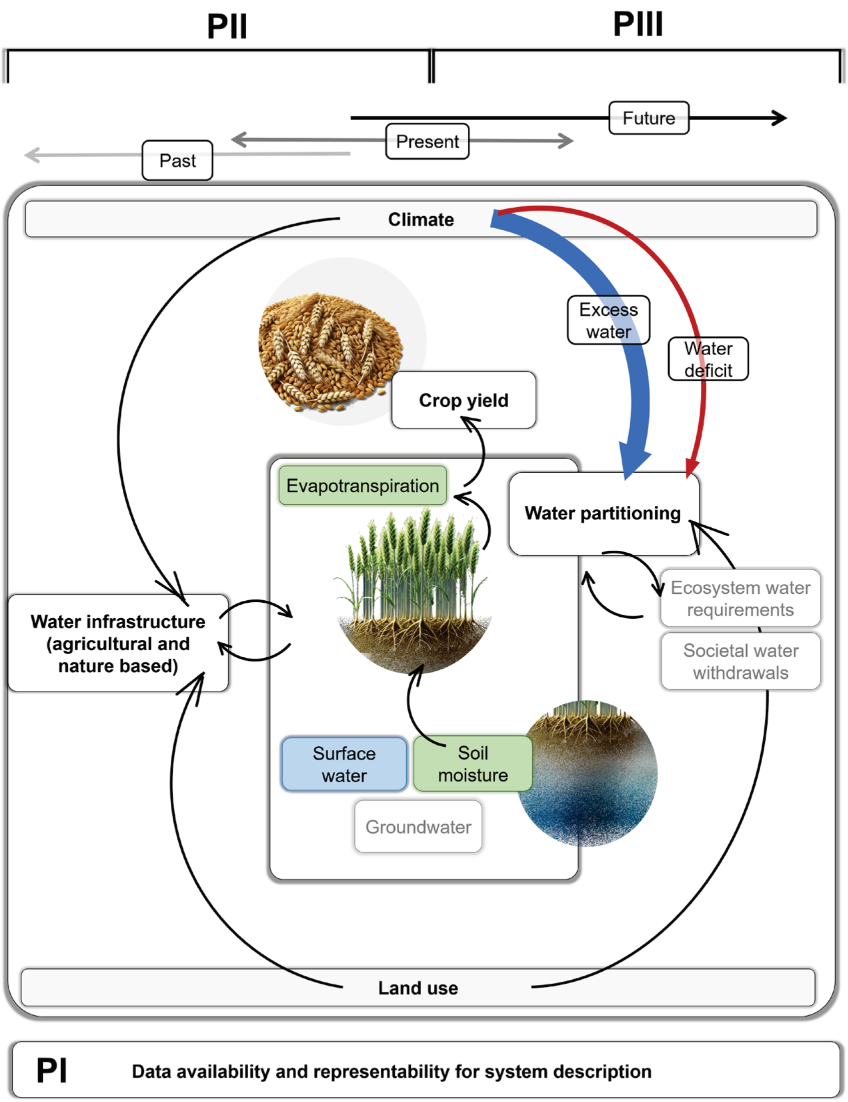

Figure 1. Schematic of connections between climate change and conditions and processes in the water balance. The dashed ellipses represent the focus of the three **Paper I**, **II** and **III** summarised in this thesis. The grey variables are not directly addressed in this thesis. Yet, they are included as important parameters affecting catchment water allocation and indirectly affect water availability for agriculture, which is the focus in this thesis. “Ecosystem water requirements” refer to water levels and flow required to sustain ecosystem within the system boundaries set to the water balance. “Societal water withdrawals” include water for industry and households

3. Background

This chapter outlines the background review to key concepts in this thesis, related to the catchment water balance, describes the link between agricultural yield, soil, and water, provides an overview of extreme weather indicators and their implications, and, lastly, synthesizes changes shown to the Swedish water balance in previously published studies.

3.1 Yield gaps

Crop production is dependent on climatic conditions and interactions between weather variables. The potential yield (Y_p) is the highest yield possible for crop species and varieties determined by biophysical and genetic constraints only. This is the yield for a crop grown under favourable conditions without water or nutrient limitations, and controlled conditions for biotic and other abiotic stresses, only dictated by local weather conditions and soil properties. Thresholds for the weather variables determine Y_p. These thresholds vary between crop species, cultivars and crop growth stages.

The absolute yield gap (Y_g) is the difference between potential yield (Y_p) (optimal irrigated systems) and actual observed crop yield (Y_a) (Eq. 4) or between water-limited yield (Y_w) (rainfed systems) and Y_a (Eq. 5) (Sadras et al., 2015).

$$Y_g = Y_p - Y_a \qquad \text{Eq. 1}$$

$$Y_g = Y_w - Y_a \qquad \text{Eq. 2}$$

The water limited yield gap (Y_w) is the feasible yield in rainfed systems where the water supply is limited. Actual yield (Y_a) is the observed yield, limited by stresses such as limited water- and nutrient supply, biotic stresses, e.g. pests and diseases, the local climate and the management skill of the farmer (Sadras et al., 2015). However, due to practical limits to enable sustainability in the production, caused by environmental legal regulations and the farmer's financial resources to spend on inputs such as nutrients and pesticides, the exploitable yield gap is considered to be 80 % of Y_p or Y_w.

Overall, four methods are used to estimate Y_p and Y_w (i.e. field experiments, yield contests, surveyed maximum yields and simulations by crop models). The estimates are often presented as ranges of likelihood due to spatial variation in soil properties, intra-annual variation in weather and, if based on empirical data, variations in crop management methods between farmers. This leads to potential over- or underestimation of the actual yield gap (van Ittersum et al., 2013). Note, that the concept of water limited yield is linked to crop water deficit. There is no such frame work for effects of crop water excess, although it has been shown that conditions of excess water (i.e. soil saturation/flooding) can possibly equal the effect on reduction of yield quantity and potentially quality.

The correlation between weather and yield reduction and their importance for the estimation of yield gaps varies with season and regions of the earth (Li et al., 2023; Vogel et al., 2021). The physiological stress response of a crop to sequences of extreme weather events can result in crop damage that would not occur due to the stress response for one individual weather event (Lesk et al., 2022).

For more detailed overviews of mechanical, physiological and biotic stress response toward crops, further reading can be found in Kaur et al., (2020).

3.2 Extreme weather and extreme events as challenges to agricultural production

For a definition of extreme weather to be of value concerning crop production, variables describing growth, development, germination or survival of crops should be included (Barlow et al., 2015). Definitions of agro-meteorological extremes include the relationship between weather impacts (direct and indirect) on crop yield and related requirements on cropping conditions. Extreme weather events include two dimensions, the occurrence or probability that the event occurs, and the duration and/or intensity (McPhillips et al., 2018).

Extreme weather events do not necessarily lead to a hazard (here defined as a “climate-related phenomenon before a potential impact”, Zscheischler et al., 2020) for a defined system. For example, an extreme rainfall does not have to lead to a hydrological flood (Zscheischler et al., 2020). In contrast, non-extreme weather events can act synergistically and cause extreme impact, resulting in so-called compound extreme events. A compound event is two or more consecutively occurring events, or a synergistic simultaneous occurrence of two or more low-frequency events. For instance, high temperature and low precipitation (e.g. climatic variation) may together create conditions for a hazard, such as a drought, depending on location preconditions that lead to an impact, e.g. loss of crop yield (WMO, 2010; TT-DEWCE WMO, 2016; Zscheischler et al., 2020).

Quantitatively, extreme weather is defined by thresholds based on observed distributions of weather events, their impact on important sectors, e.g. agriculture or industry, or parameters or various indices (Seneviratne et al. 2012; TT-DEWCE WMO 2016). The thresholds are calculated from historical data of these events or factors, including statistically rare values or events where one or more sectors (e.g. agriculture) experience a negative impact (e.g. yield loss) (TT-DEWCE WMO 2016). Extreme events are usually defined by statistical frequencies (often within the limits of the < 10^{th} and > 90^{th} percentiles, or even lower limits e.g > 70^{th} percentile) of a historical dataset, or defined by temporal return periods e.g. 10 year, 100 year (Bärring et al., 2006; Fleig et al., 2011).

In Malmquist and Barron (2022), definitions of indices for extreme events were event. Linked to agriculture and crop production in the temperate-boreal zone. In the review we concluded that there was a lack of consistency and common standardization of indices, and that these indices related to impact of temperature and precipitation tended to show a wide variety of temperature ranges and water volumes (Malmquist and Barron 2022). We concluded that although the numerous indices serve different purposes depending on the research objective, there was a lack of consensus on definitions and on what was meant by “extreme” in respective publication.

3.3 Water retention properties of soils

The two main variables governing water flows and water retention capacity in soils are hydraulic conductivity and water holding capacity. Soil infiltration, flow and storage of soil water as well as accessibility of water and oxygen for plant uptake is dependent on e.g. textural porosity (pores being a function of particle size) and structural porosity (pores created by physical, chemical or biological properties or disturbances. From pedon scale to regional scale, soil forming processes are depending on parental material, biological disturbance from soil organisms and vegetation, topography, climate and time) (van Breemen 2004). Structural and textural porosity is in turn dependent on variables such as soil organic carbon content, biological activity, compaction, freeze-thaw intervals, mineral exchange, swelling and chemical reactions, aggregation, previous level of soil moisture and anthropogenic disturbances through soil management such as tillage (Rabot et al., 2018, Chan, 2011), where soil compaction alters properties such as the pore size distribution which in turn changes water retention and hydraulic conductivity (e.g. Lipiec et al., 2012).

Climate

Indirectly, precipitation and changes in temperature affects soil properties, which in turn can impact availability, distribution and partitioning of water. Changes in weather patterns can impact soil macroporosity, i.e. major structures for infiltration and flows of larger water volumes (Alaoui et al., 2011). Drier conditions increase macroporosity, while colder and more humid climate might lead to decreased macroporosity (Hirmas et al., 2018). Changed weather patterns leading to increased water availability additionally affect overall soil pore-size, soil cracks and clogging of pores by increased plant-root growth (Caplan et al. 2019). Dry spells on the other hand can lead to altered root development and increased cracking of the soil which impacts soil infiltration characteristics. Longer dry spells can result in hydrophobic soils, leading to increased preferential flows despite unsaturation of the soils (Robinson, 2018). In the Nordic region, freeze-thaw cycles effect have shown to increase near-saturated hydraulic conductivity, with potential to increase drainage capacity at plot-scale. Furthermore, regionally, soils under higher temperature and higher precipitation regime have shown less developed soil structure, i.e lower pore-size distribution (Klöffel 2024).

However, evidence for the local- and regional impact of soil parameters on hydrological cycling could be limited on a global scale, either due to the fact that these parameters are masked on a global scale or the resolution of global models does not capture the spatial heterogeneity well enough, to account for regional effects (Fatichi, et al., 2016). For a further description of the connection between soil properties and hydrology from pedon to catchment scale, see Veerecken et. al. (2022). Vegetation have been suggested to be the main control on water balance over scale yet through a two-way link between vegetation arrangement over scale and soil moisture availability and the higher -or lower flow interconnectivity between catchment regions (Thompson et al., 2011).

3.4 Water balance for agricultural landscapes

The water balance equation [Eq. 1] is based on the law of mass conservation. The change in water storage equals the difference between water inflow and outflow (Chapin et al., 2011). Depending on the defined spatial and temporal scale alongside the theoretical system boundaries, e.g. sub-basin, catchment or larger, some incoming and outgoing flow variables, such as industrial, agricultural or urban water use or wastewater discharge, are sometimes excluded. However, internal catchment flows are intrinsically linked to other catchments and global water circulation (Abbott et al., 2019b). Consequently, in its full form, the water balance equation also includes inflows/outflows from/to external hydrological units and internal flows.

$$P + R_{\text{in}} + L_{\text{in}} + Gw_{\text{in}} + In + Pn + It + Ex_{\text{in}} + RET = R_{\text{out}} + ET + L_{\text{out}} + Gw_{\text{out}} + C + Dr + ABS + Ex_{\text{out}} + \delta S \quad \text{Eq. 3}$$

(European Commission 2015)

In [Eq. 1], inflow is represented by precipitation (*P*) and external inflows from surrounding hydrological units by surface inflow (R_{in}), lateral subsurface drainage inflow (*L*in) and groundwater inflow (Gw_{in}). Outflows include surface runoff (*R*out), lateral outflow (*L*out), groundwater outflow (Gw_{out}), soil and water evaporation and crop transpiration (*ET*). The change in storage (δ*S*) is defined as the difference between inflow and outflow. Connective flows include infiltration (*In*), percolation (*Pn*), drainage below the root zone (*Dr*) that recharges groundwater stocks, and interception (*It*) by crop foliage and capillary rise (*C*). The latter connects soil water stocks with above-ground outflows, facilitating crop water uptake and thereby transpiration and evaporation from bare ground. The anthropogenic impact on the water cycle includes inflow (Ex_{in}) and outflow from external units Ex_{out} (not included in incoming and outgoing surface flow, lateral flow and groundwater inflow respectively). The term *ABS* includes water abstraction from water resources within the hydrological unit that affects other flows, yet is circulated within the catchment. Over a more extended period, *ABS* is either returned (*RET*) to flows within the catchment or leaves the catchment via outgoing flows (see, e.g. European Commission, 2015). One example where the term *ABS* is important is to account for water abstraction for irrigation, where water is excluded either by evapotranspiration or excess irrigation, and water re-infiltrates to subsurface water and groundwater and is available for use further downstream (Grafton et al., 2018).

A change in the storage term (δS) is related to the water's retention time within the system boundaries and includes the term transit time (τ_w). Transit time (τ_w) can be described as the time for a unit of water from the catchment input boundary (t_{in}) to travel to the output boundary (t_{out}) (Eq. 2). The mean age ($\tau_{w,a}$) of the water unit can be defined as the difference between time at sampling of the water unit ($t(x_w)$) and the time at inflow (t_{in}) (Eq. 3).

$$\tau_w = t_{out} - t_{in} \qquad \text{Eq. 4}$$

$$\tau_{w,a} = t(x_w) - t_{in} \qquad \text{Eq. 5}$$

(McDonnell et al., 2010)

There are different temporal responses of fast (surface flows and flows in the unsaturated zone), as well as slow responding pathways (deep groundwater flows) (McDonnell et al., 2010). In addition, there can be a variation in magnitude and seasonal variations in the occurrence of precipitation and snow-melting events that, together with the state of the catchment (e.g. dry, snow-covered), affect the transit time between input and output (Heidbüchel et al., 2012).

In comparison to Eq. 1, the hydrological model used in **Paper II** and **Paper III**, the Soil and Water Assessment Tool (SWAT+) base the land-based water cycle on a description of the water balance distinguishing the flow variable into surface runoff (Q_{surf}) and return flow (Q_{gw}) from groundwater. And include the variable w_{seep} that represents the water volume percolating and exiting the bottom of the soil profile per time step (Eq. 6) (SWAT development team 2024).

$$P = Q_{surf} + ET_a + w_{seep} + Q_{gw} + \delta S \qquad \text{Eq. 6}$$

This model is further complex in the model structure where surface runoff is additionally divided into lateral flow tile flow and surface runoff. Groundwater is divided into shallow and deep aquifers, where just the shallow aquifers contribute to the groundwater return flow (Q_{gw}), while outflow from the deep aquifer is excluded from the future calculations. External inflows can be added as inlets and abstraction can be added as internal flows or as point sources extracted to outside the catchment ().

For the remaining of this thesis, the focus will be based on the simplified water balance, yet with the runoff combined into the variable Q (Eq. 6).

3.5 Mitigation and adaptation interventions for improved water retention

Mitigation and adaptation interventions for water management can be divided into nature-based (or so-called green infrastructure) measures and engineered measures (also commonly referred to as grey infrastructure). There is an overlap between the concepts. Nature based solutions (NBS) are intended to restore or improve existing water infrastructure or functions by enhancing (or mimic) ecosystem services processes. Engineered measures on the other hand involves construction of new structures to improve one or a limited set of ecosystem functions (Eggermont et al. 2015; Iseman and Miralles-Wilhelm, 2021, p.11). Catchment systems engineering (CSE) is a broader category that includes both grey and green infrastructure. However, this concept is more conservative concerning restoration due to the recognition of landscapes that have already been modified through historical and present day anthropogenic alterations (Hewett et al., 2020).

Mitigation/adaptation interventions can either be structural or time-sensitive practices used during the cropping season to improve both water quality and quantity. Rittenburg et al. (2015) grouped so called best management practices directed towards water quantity into two groups. They either aim to increase the infiltration and storage capacity of the soil or to reduce the flow velocity of overland flows. The efficiency of best management practices on both water quantity and quality varies according to the season and the local site conditions (e.g. soil properties and topography) (Liu et al., 2017; Rittenburg et al., 2015).

Nature-based solutions (NBS) are measures inspired by natural processes and/or structures (European Commission, 2023; IUCN, 2016) that aim to…

> "… protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while

> simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits…" (UNEP/EA.5/Res.5, 2022, p.2).

The definition of NBS varies between institutions and leaves different room for engineering of certain interventions (Cohen-Shacham et al., 2016). It has been emphasised that NBS cultivate and manage natural processes, and the physical system design does not necessarily need to be a design naturally occurring in nature (WWAP/UN-Water 2018).

The report Nature-Based Solutions for Water (UNESCO, 2018) defined NBS linked to water as:

> "…inspired and supported by nature and use, or mimic natural processes to contribute to the improved management of water. The defining feature of an NBS is, therefore, not whether an ecosystem used is 'natural' but whether natural processes are being proactively managed to achieve a water –related objective."

(UNESCO, 2018, p 22)

From a water management perspective, NBS typically target for instance water storage, regulation of water quality and water retaining functions in the landscape (e.g. flood prevention). The targeted variables either impact water flows and stocks directly (e.g. wetlands or re-meandering of waterbodies) or indirectly by altering local and landscape factors (e.g. soil physical properties or vegetation that affects green water- and blue water distribution and retention time in the landscape) (UNESCO, 2018). While NBS is a relatively new term (Cohen-Shacham et al. 2016), it includes practices that have been around for centuries. With the current UN-Decade of Ecosystem Restoration (A/RES/73/284 2019) their practice get interlinked with new interventions. It should be mentioned that NBS can be considered an umbrella concept covering multiple measurement categories with different targets and implementation scales, while there are additional overlapping concepts with a more explicit aim to promote water retention and facilitate water storage (Magnier et al., 2024).

In Sweden, NBS have been implemented for more than 30 years. The majority of implemented NBS have aimed to reduce non-point sources of nutrients to improve water quality from field to catchment (the Water

Authorities et al. 2024). However, due to increased frequency and intensity of drought events and flooding, discussions of multifunctional landscapes and measures have emerged.

3.6 Evidence base for water partitioning in Sweden's arable landscapes

The below section presents a review of water balance changes over time in Swedish catchments, considering the variables precipitation (P), streamflow (Q) actual evapotranspiration (ET_a) and the difference in soil water storage (δS) (Eq. 6).

Studies on Sweden's water balance vary in their coverage of water balance variables. While historical and future streamflow and evapotranspiration changes have been well defined, water storage such as soil moisture are less explored in scientific literature and studies have mainly been done in mixed land use or forested catchments. In addition, there are fewer studied catchment on mesoscale (e.g. 10^1 to 10^3 km^2 (e.g. Uhlenbrook et al. 2004).

3.6.1 Precipitation

The annual precipitation in Sweden has increased by approximately 100 mm nationally on average (from approximately 600 to 700 mm) since the middle of 1970. Especially during winters, by approximately 50 mm since the end of the 20th century; this increase mainly occurred between 1961-1990 and 1991-2020. The largest increase of annual precipitation was observed in northern Norrland, and in the counties Västra Götaland, Bohuslän and Halland (Schimanke et al., 2022).

3.6.2 Streamflow

Streamflow change over time show spatial and inter-annual variation, yet with potential for regional generalization of streamflow patterns. Sweden has historically experienced a trend of increased streamflow throughout the country with shorter and fewer hydrological drought events, except for catchments in southern Sweden that have experienced a drying trend during spring- and summer (Teutschbein et al., 2022). Especially during winter, south-westerns Sweden indicate significant wetting trends (Teutschbein et al., 2022) (Figure 2). Velde et al., (2013, year 1961-2010) confirmed a drying trend in south-east Sweden, while they observed increased streamflow in the south-west. On the contrary, Destouni et al., (2013) and Destouni and Verrot (2014) observed decreased streamflow in agricultural catchments in central Sweden (Norrström, Vättern and Vänern, 1901-1930 and 1971-2000) but increased streamflow in northern Sweden (Piteälven). Older studies have shown an increased streamflow with increased share of agricultural area (Andersson and Sivertun., 1991). Intra-annual trends have been shown by Hogland, (1994) with varying runoff from different land use depending on season. Yet agricultural land contributed the most on an annual basis.

In addition to the temporal change in mean streamflow between locations, there has been a variation in streamflow variability. Increased streamflow variability was observed in 59 out of 79 observed catchment by Åkesson et al. (2016), between 1993-2013, in 3 catchments in central Sweden by Destouni et al., (2013) and by Bogaart et al., (2016) in north-and southeast of Sweden, while increased retention time and no change in flow variability were observed in southern catchments.

Streamflow variation during the 20[th] century has overall been concluded to be more related to changes in land use and biomass and to variation in ET_a than to shifts in temperature or precipitation (Åkesson et al., 2016; Andersson and Sivertun, 1991; Destouni et al., 2013; Velde et al., 2013) as well as stream recession time (Bogaart et al., 2016). Indeed, a limited effect of historical climate change on streamflow was detected by Arheimer and Lindström, (2019), who compared the periods 1961-1990 and 1970-2010. A more recent study by Teutschbein et al. (2022) showed impact on streamflow in catchments and sub-basins in response to changes in the precipitation regime and a reduction of snow cover with warmer climate and drier conditions during spring and summer in southern Swedish catchments. Similarly, Bring et al., (2015) showed increased streamflow and reduced evapotranspiration due to increased temperature (period 1961-1990). Lastly, Hu et al., (2023) showed an overall positive relationship between precipitation and water yield (volume of P not allocated to ET_a) as well as temperature and water yield between the years 2003-2018.

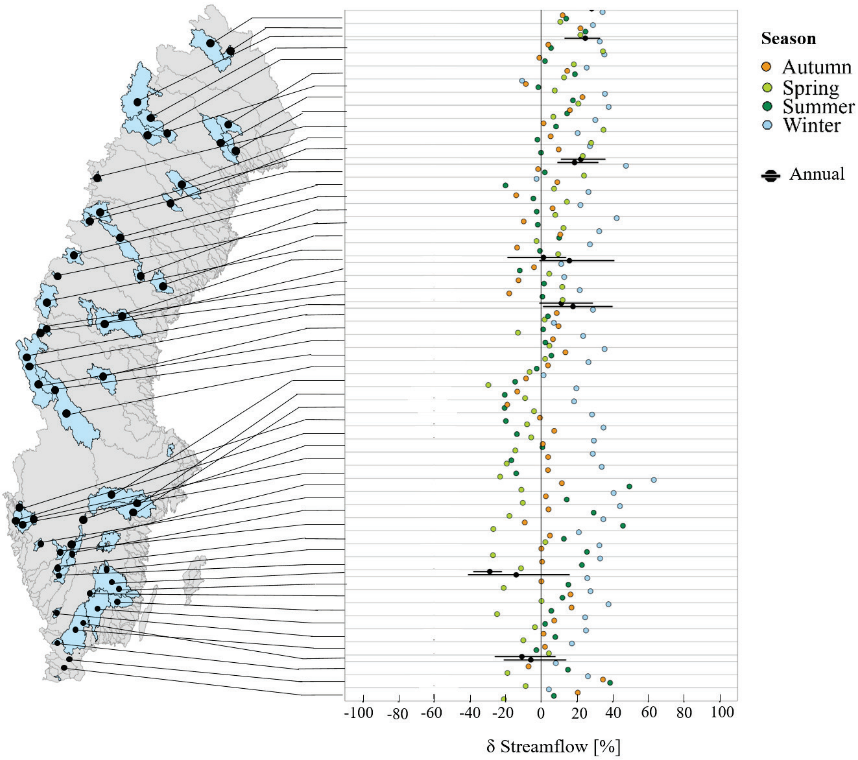

Figure 2. Observations (comparing 1961-1990 to 1991-2020) of historical change in average streamflow in Sweden. Black lines represent intervals over maximum and minimum changes over the measurement periods, Black dots represent annual average, coloured dots show seasonal (winter = blue, autumn = orange, spring = light green and summer = dark green) change between measurement periods. Values are extracted from Teutschbein et al. (2022) and Andréasson, (2004).

3.6.3 Evapotranspiration

For the first half of the 20th century, actual evapotranspiration (ET_a) has increased, which has been linked to land use change (i.e. increased biomass production) (Destouni et al., 2013; Jaramillo et al., 2013; van der Velde et al., 2014). However, there are indications that climate changes have had a possibly larger influence on ET_a since the later part of the 20th century (Destouni et al., 2013; Jaramillo et al., 2013), although considering limited spatial coverage of results (Figure 3).

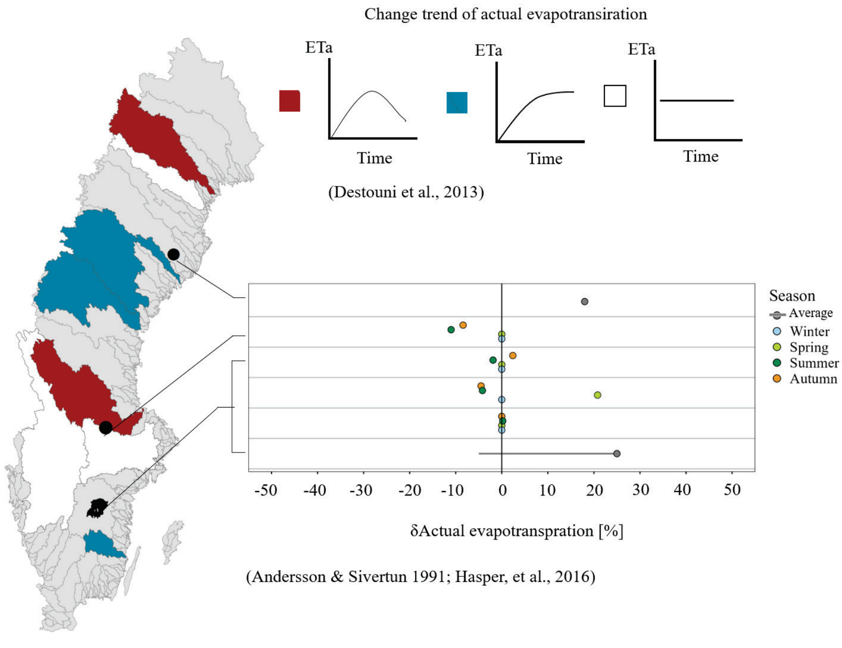

Figure 3. Trend in evapotranspiration 1920-2000 (Destouni et al., 2013) and evapotranspiration change 1870-1980 and year 1961-2012 (Andersson & Sivertun 1991; Hasper, et al., 2016). The small graphs show the schematic trend in actual evapotranspiration (ET_a) over time 1920-2000. Red indicate a decreasing trend in ET_a, blue indicate an increase in ETa over time and white indicate an overall stagnant ET_a over time.

Streamflow and ET_a under historic climate change scenarios also indicate spatial variation in changes with increased streamflow in north and reduced in South/southeast Sweden (Arheimer and Lindström, 2015; Bergström et al., 2001). Nationally, ET_a has been shown to increase concurrently with precipitation increases (Velde et al., 2014, the year 1961-2010). Regions in western Sweden have tended to stretch to more energy limited, i.e., sufficient water availability but without sufficient incoming energy to support evapotranspiration of the entire water availability. On the contrary, in the east, energy is sufficient for increased evapotranspiration, yet there has been limited water availability to meet the possible higher evapotranspiration (Velde et al., 2014).

3.6.4 Soil moisture

Simultaneously with increased precipitation and reduced surface runoff, Destouni and Verrot, (2014) (Norrström Basin, comparing 1950-1969 to 1990-2009) observed a decrease in soil moisture especially between March to October. However, neither intra-annual fluctuations nor inter-annual mean shifted significantly (Destouni and Verrot, 2014). Both extreme dry (< 1st percentile of soil moisture content, base period 1901-1920) and extreme wet (> 99th percentile of soil moisture content, base period 1901-1920) increased over the century to 1990. Yet, the dry area increased 10 times the increase of wet area, despite a precipitation increase over time (Destouni and Verrot, 2014).

Verrot and Destouni (2015) explored soil moisture in the unsaturated zone (using a 1D model over 2.5 m soil depth) in the catchments Piteälven (northern Sweden) and Norrström (south-eastern Sweden) between 1950-1969 and 1990-2009. They found a spatial difference with increased peak soil moisture in the northern Piteälven due to increased recharge from increased snowmelt, which maintained soil moisture levels throughout the following summer. In Norrström, decreased precipitation in the form of snow reduced the long-term recharge, leading to less soil water in spring and summer, and larger soil moisture fluctuations over the year. Variation between seasons indicated higher soil moisture variability than between years (Verrot and Destouni, 2015).

Comparing soil moisture stress from the 1960s to the 2020s in Sweden show decreased stress over time (Teutschbein et al. 2024 see their Fig. 4, ERA-5 Land reanalysis dataset. Soil moisture calculated through water balance model with weather data as input). Linking soil moisture stress to precipitation deficit showed that in 48% of the cases of precipitation deficit, soil moisture drought occur. The largest probability of soil moisture drought (considering the topsoil 0-7 cm) after precipitation deficit occurred in the summer, with on average a 68% probability of soil moisture deficit occurring within one month of precipitation deficit (Teutschbein et al. 2024). The central areas of Sweden show the highest difference from 1960s to 2020s of increased soil moisture under current climate. However, three months accumulated soil moisture index for southern Sweden (Götaland and southern Svealand) showed an increase in soil moisture drought between the periods 1961-1990 and 1991-2020 (Teutschbein et al. 2024).

3.6.5 Estimations of water balance change with climate change

On annual basis, southern Sweden indicated reduced precipitation in the south but increased precipitation in the rest of the country for low emission scenarios, while the higher the emission scenario, the increased precipitation (Teutschbein et al. 2023).

Streamflow explored under climate change scenarios have shown increased streamflow in north and reduced streamflow in south/southeast Sweden (Arheimer and Lindström, 2015; Bergström et al., 2001) (Figure 4 During the cropping season, Grusson et al. (2021b) showed that runoff for three catchments in south (Skåne), east (Östergötland) and western Sweden (Västergötland) is expected to increase, especially during the middle of the cropping season, while being stagnant (south) or decreasing in the start and end of the cropping season.

Evapotranspiration under impact of climate change is expected to increase (Bring, 2015; Grusson et al., 2021b; Jaramillo et al. 2021; Xu, 2000; Xu and Halldin, 1997), which have also been shown considering the index SPEI, (an index combining precipitation and evapotranspiration and compare to historic values) with increased drying except from central-eastern Sweden (Teutschbein et al. 2023). These trends are projected irrespective of using different climate models and generations of emission scenarios as drivers and time comparison.

Overall lower transit time of water in the landscape have been estimated (Velde et al., 2014), as well as temporal shifts of seasonal flows to earlier and lower spring flows and higher magnitude of autumn flows (Arheimer and Lindström, 2015; Bergström et al., 2001; Destouni and Verrot, 2014; Teutschbein et al., 2011, 2018; Xu and Halldin, 1997). National estimates from downscaled climate models (CMIP5, RCP4.5 and RCP8.5) indicated an increased soil moisture content during 2050-2070 in eastern Svealand and central to western Götaland, while a decrease was predicted for the rest of the country, which was expected to become most severe in north-eastern Norrland (Jaramillo et al. 2021). At catchment scale, Grusson et al. (2021 b), (Scenario RCP4.5 and RCP8.5, period 2021-2080, reference period 1971-2000) showed decreased or stagnant soil water content despite increased precipitation. The change/stagnant level of soil water content was related to increased ET_a in the catchments in Skåne (8.24 km^2) and Västergötland (9.31 km^2).

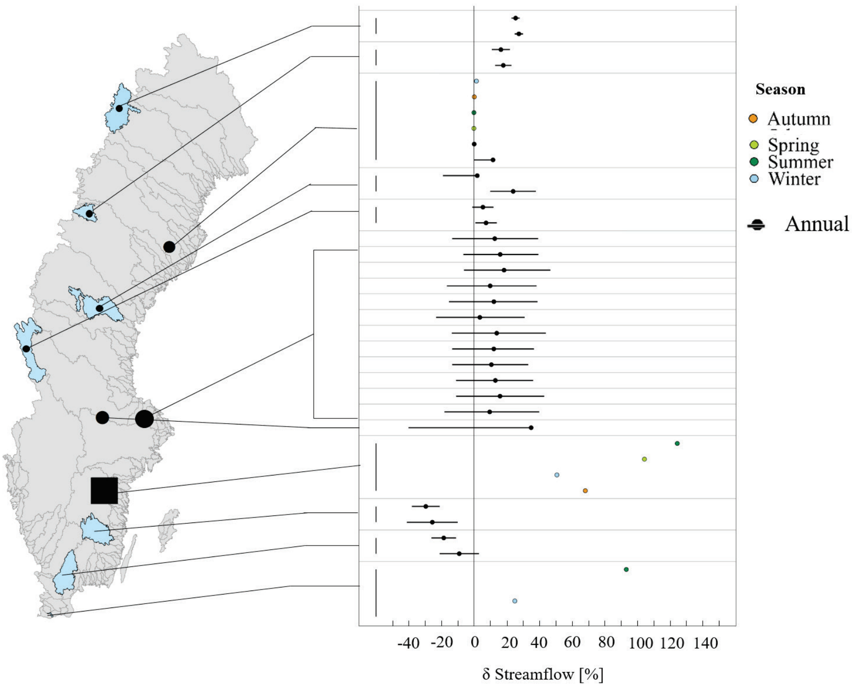

Figure 4. Average change in streamflow under impact of climate change. Values are compiled from Bergström et al. (2001a) (a 30 year undefined period of climate change impact); Arheimer & Lindström. (2015) (scenario for year 1970-2100); Teutschbein et al.. (2011) (Scenario 2071-2100); Teutschbein et al. (2018) (Scenario 1981-2010 to 2061-2090); Xu (2000) (Hypothetical climate change scenarios changing temperature and precipitation); Xu & Halldin (1997) (Hypothetical climate change scenarios changing temperature and precipitation); Bieroza et al. (2024) (change between 1995-2023 and 2024-2099, median Q).

4. Material and method

This chapter presents the properties of the catchments used in **Papers I-III**, indata and the method used in **Paper I** and describes data modifications and model setup for suitability in the Soil and Water Assessment Tool (SWAT+) used in Paper **II** and **III**, and describes the model itself. Lastly, the chapter includes descriptions of methods used for statistical analysis. In summary, in **Paper I** methods where developed combining available dataset to improve spatial representation of the soil physical properties water holding capacity (AWC), saturated hydraulic conductivity (K_s) and bulk density (BD); natural streams and ditch network; and spatial representation of waterbodies in the four catchments. In **Paper II** historic water balance was modelled with result focusing on streamflow/water yield, evapotranspiration and net effects to these flows by including historical waterbodies and streams in current land use and climate. In **Paper III,** future climate scenarios (2021-2060) were modelled to explore effects of climate change on soil moisture and evapotranspiration as a proxy for crop yield.

4.1 Study area

Four catchments were selected as examples in this thesis: Enköpingsån-Örsundaån, Loftaån-Gamlebyån, Saxån-Braån (**Paper III**), and Tidan (**Paper I, II and III**) (Figure 5). These catchments represent key areas of agricultural production with distinct temperature and precipitation regimes (SMHI, 2022) (Figure 6), soil types, production systems and land cover (Malmquist, 2021). Saxån-Braån, which is located in southern Sweden has a higher normal[ii] temperature, while the higher precipitation is in the Tidan catchment (Table 1). The proportion of agricultural land is highest in Saxån-Braån (75 %) and lowest in Loftaån-Gamlebyån (10 %). The soils in the Tidan catchment are mixed, consisting of silty clay loam, loam, sandy loam clay loam and silt loam. Saxån-Braån include coarser soils while Enköpingsån-Örsundaån and Loftaån-Gamlebyån consists of more clay soils

[ii] Normal periods are generally 30 year periods that describe the average (normal) climate at a certain location. Weather variables (e.g. temperature, precipitation) is compared to the normal values and analysed as anomalies to this period. The current normal period is year 1991-2020 (Baddour & Kontongomde (eds), 2007)

(Table 1) (Malmquist, 2021). These four catchments were chosen from catchments used in the former project LEVA (Local engagement for water), an initiative to improve water quality from a catchment coordination perspective of multiple stakeholders[iii]. Despite the fact that activities for improved water management (quality and quantity) have reached different stages in the catchments, they represent forerunners for catchment management in Sweden.

[iii] https://www.havochvatten.se/lokalt-engagemang-for-vatten

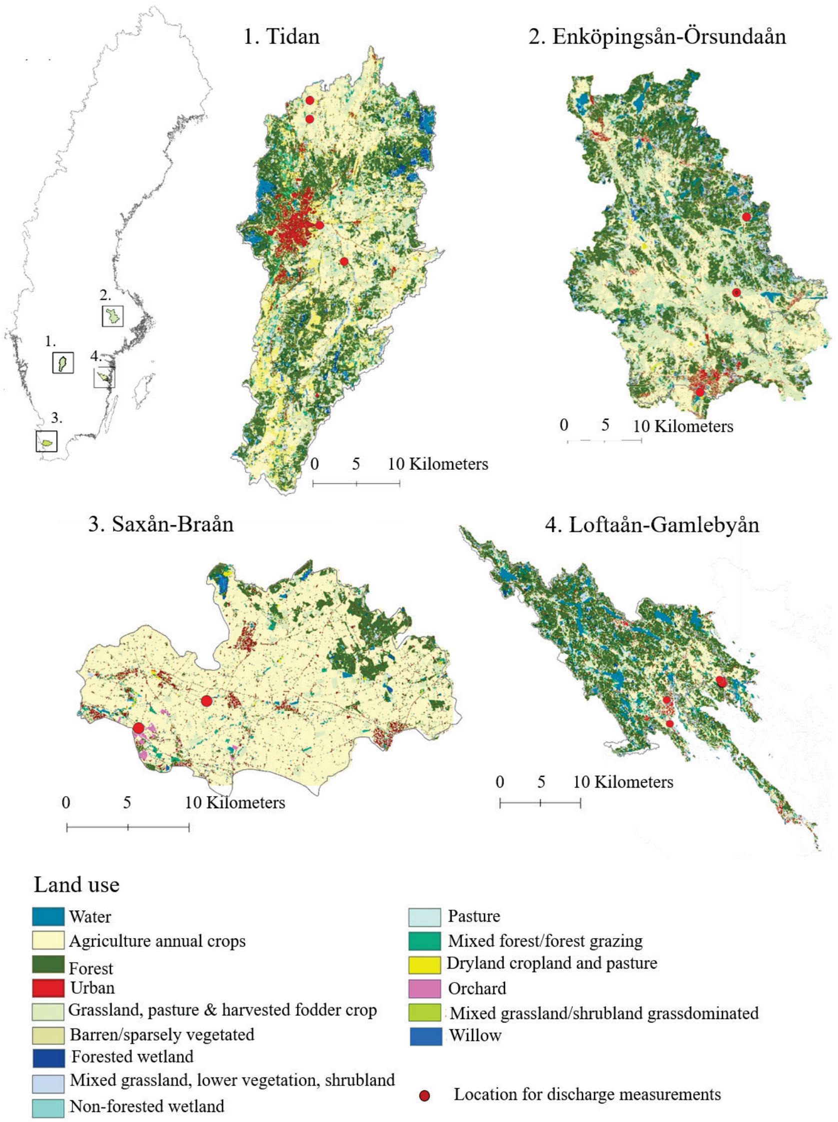

Figure 5. Location and land use of the four catchments used in methodological approach (**Paper I**) hydrological modelling of historical landscape (**Paper II**, catchment no.1, Tidan) and **Paper III** (catchments no. 1-4, Tidan, Enköpingsån-Örsundaån, Saxån-Braån and Loftaån-Gamlebyån). Adapted from Malmquist & Barron (2024).

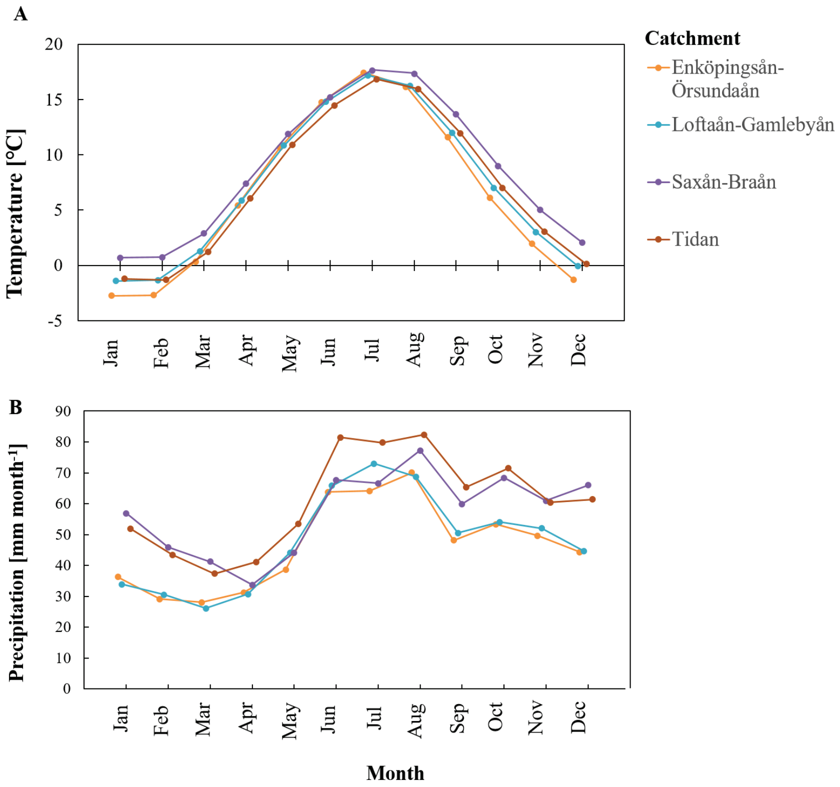

Figure 6. Normal temperature (**A**) and precipitation (B) for the normal period 1991-2020 for the catchments Enköpingsån-Örsundaån (3 stations), Loftaån-Gamlebyån (5 stations), Tidan (5 stations) and Saxån-Braån (3 stations). Figure adapted from **Paper III**, based on data from SMHI, (2022).

Table 1. Location and climatological properties for the three catchments Tidan, Saxån-Braån and Loftaån-Gamlebyån, extracted from **Paper III**.

Catchment	**Enköpingsån-Örsundaån**	**Loftaån-Gamlebyån**	**Tidan**	**Saxån-Braån**
County	Uppland	Småland	Västra Götaland	Skåne
Location	59.83°N, 17.0°E	57.96°N, 16.30°E	58.37°N, 13.92°E	55.96°N, 13.14°E
Pedoclimatic zone[i]	Boreal to sub-boreal IV	Sub-Oceanic IV	Northern sub-continental IV	Northern sub-continental IV
Area	995 km^2	725 km^2	696 km^2	359 km^2
Average monthly normal temperature[ii]	-3.1 to 18.2 ℃	-2.0 to 17.7 ℃	-2.0 to 17.6 ℃	0.0 to 18.2 ℃
Normal precipitation[iii]	559 mm yr^{-1}	574 mm yr^{-1}	710 mm yr^{-1}	689 mm yr^{-1}
Average groundwater depth [d]	1-15 m	2-7 m	0.1 – 10 m	2-7 m (year 1980-2023)
Agricultural land	35%	10%	36%	75%
Soil type	silty clay, clay loam, silty clay loam and clay,	clay, clay loam and loam	silty clay loam, loam, sandy loam clay loam and silt loam	sandy loam and loam

i Tóth et al. 2017
ii SMHI 2022
iii. SGU 2023, average depth for year 1991-2023

4.2 Indata

The hydrological model Soil and Water Assessment Tool (SWAT) used in **Paper II** and **Paper III** requires minimum indata on elevation, soil physical properties, land use and weather. These data, along with catchment-specific management techniques and structural measures on agricultural land (Appendix, Table A 1 and Table A 2); crop-specific parameters (e.g. sowing dates, days to maturity, leaf area index) valid for Swedish conditions; natural- and manmade water bodies, ditches and streams (the latter analysed in **Paper I**) were collected from national agencies, peer-reviewed publications, satellite data and grey literature. In addition, adjusted data on stream-ditch networks, waterbodies (natural and engineered), dams and subsurface drainage[i] were included in **Paper II** and **III**, based on the method from **Paper I** (see section 4.3). Water bodies from historical maps were added to land use maps as separate land use classes in **Paper II.** In **Paper III**, management practices and structures with potential effects on water storage or water buffering capacity were included as spatial objects or management practices in the models. For the full datasets and references see Table 1 and 2 in **Paper I**, Table 2 in **Paper II** and Table 3 in **Paper III**.

All spatial analysis and preparation of indata was done in ArcMap 10.8.1 and 10.8.2 (ESRI, 2021), QGIS 3.22.9 (QGIS Development Team, 2021), Excel 2016 (Microsoft Corporation, 2016) and RStudio (version 2023.03.0 build 386, R Studio Team, 2023).

4.3 Soil and Water Assessment Tool (SWAT+)

To explore the effects of historic water bodies and streams in current climate and land use on streamflow, percolation and evapotranspiration (**Paper II)** and the effect of future climate on soil moisture and evapotranspiration (**Paper III)** a modified version of The Soil and Water Assessment Tool was used (version SWAT+ 2.1.4 REV60.5.7) (Bieger et al., 2017). This model is

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[i] In literature, subsurface drainage and tile drainage is used interchangeably. However, as the term tile drainage technically defines the (mainly historical) use of clay pipes, throughout this thesis we use the term subsurface drainage to undoubtedly also include pipes of modern material such as PVC, corrugated plastic and others.

a semi-distributed[ii] and process-based model, with incorporated functions for hydrology (Section 3.4, Eq. 6), groundwater, dynamic crop growth, nutrient transport, pesticide transport and soil erosion.

The model is among the most widely used hydrological and water quality models (Fu et al., 2019). SWAT has been used for several model setups of extreme high- and low flows, largely used in the USA and China, for larger basins, and on a national scale. Hence, there is room to explore the use of the model at more northern latitudes and to develop uncertainty analysis in modelling of extreme events (Tan et al., 2020). Compared with other models, SWAT has shown a good representation of annual water dynamics. Still, SWAT has shown limitations in representing flow variation on a shorter time scale (Farkas et al., 2016; Piniewski et al., 2017) and possibly peak flows (Zhang et al., 2014; Grusson et al., 2021). The model runs on daily- or sub-daily time steps.

Initially, SWAT was developed for catchment scale to predict the effects of agricultural management on catchment hydrology, sediment transport and chemical leaching (Arnold et al., 1998). The revised version of SWAT+ provides more flexibility for the user by simplifying the spatial location of objects, e.g. wetlands and ponds and the location of floodplains and upland land areas. It also offers temporal flexibility through management decision tables and allows land use changes during the model period (Bieger et al., 2017).

4.4 Processing of soil physical properties, stream and ditch network and tile drainage in GIS-software (**Paper I**)

An absence of data of soil physical properties describing the spatial distribution of infiltration and water holding capacity in the unsaturated zones was identified, while compiling data for the hydrological modelling in **Paper II** and **Paper III**. Furthermore, stream networks covering agricultural land were misaligned between datasets. Lastly, there was an absence of digitised tile drainage maps. This is an important feature due to Sweden's

[ii] Semi-distributed models separate land use into homogenous objects with similar hydrological response, so called HRUs (hydrological response units) based on common variable values, e.g. SWAT+ uses land use, soil type, topography and slope) (Fu et al. 2019)

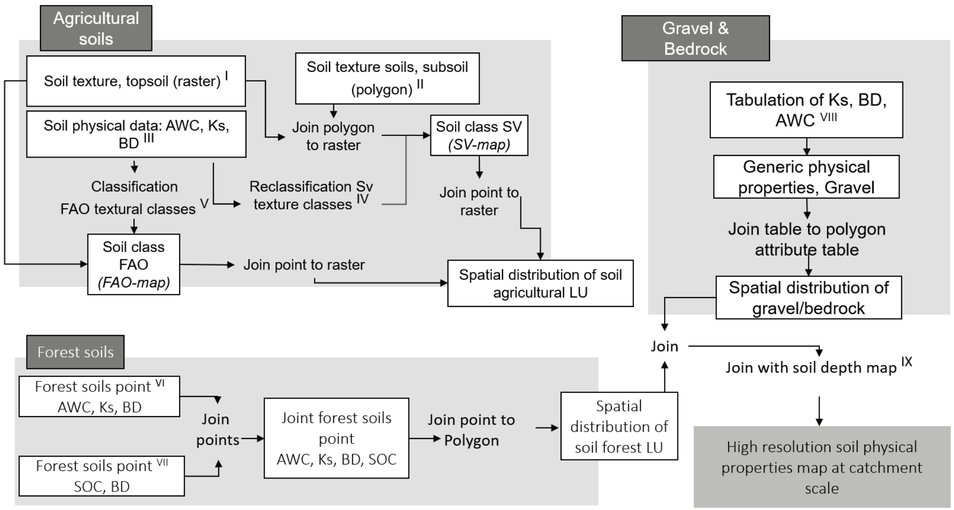
dependence on subsurface drainage in major cropping areas to sustain to maintain suitable soil moisture conditions for crop production.

4.4.1 Soil physical properties

Soil profiles with soil texture data and physical properties are available as spatial objects (raster or vector data). Yet, the data available per soil profile was not consistent with the requirements of indata for SWAT+. Hence, the below section describes our method for achieving a congregated dataset with a realistic spatial description of soil physical properties.

A spatial coverage was developed of water holding capacity (AWC), hydraulic conductivity (K_s) and bulk density (BD) in agricultural and forest soils. Point samples from the SLU soil database (Wesström and Joel 2012), soil profiles published in Karltun (1995) and the CoupModel soil database (Jansson and Karlberg, 2004) were combined. The data was classified by texture in the topsoil (10-20 cm) and subsoil (40-60 cm) in the soil texture systems of the Food and Agricultural Organization of the United Nations and the Swedish soil textural system respectively. For forest soils, soil profiles (with associated values of AWC and K_s) from the CoupModel (Jansson and Karlberg, 2004) were combined with soil profiles from Karltun (1995) (with associated BD values) based on matching soil organic carbon content (SOC) in the topsoil (5-15 cm) and the subsoil (40-60 cm), and slope location. Soil organic carbon varies with topography and soil hydrologic class (e.g. Olsson et al., 2009). Bulk density values were extracted from Karltun (1995) and attributed to the respective matching profile from the CoupModel.

The spatial coverage of soil texture was accessed from Piikki and Söderström (2019) (Åkermarkskartan, raster data, agricultural land) and Geological Survey of Sweden (2014) (polygon layer, forest and other land cover). Point data of soil physical properties for agricultural soils was spatially joined to Åkermarkskartan (Piikki and Söderström, 2019) by matching the spatially closest pairs of the same soil texture class of raster pixel and point. Physical properties in organic agricultural soils were assigned based on type of organic material, which is gyttja, fen or bog peat. Point data of forest soils were spatially joined to the same soil texture class of the closest subsoil layer (40-60 cm) from Geological Survey of Sweden (2014) for soil classes that were not classified as arable land (Figure 7).



References dataset and soil textural classification keys

I. Piikki & Söderström, 2019
II. Geological Survey of Sweden, 2014
III. Wesström & Joel 2012; Jansson & Karlberg, 2004;Berglund et al., 1989
IV. Swedish University of Agricultural Sciences, 2021b
V. Benham, E., Ahrens, R.J. & Nettleton, W.D, 2009; USDA, 2017
VI. Jansson & Karlberg, 2004
VII. Karltun et al., 1995
VIII. Vägverket & Räddningsverket 1998; Ferdos et al., 2015; Mulqueen, 2005, Zhang et al., 2010; Li et al., 2021, eds. Göransson, 2014; Carlsson & Carlstedt, 1977
IX. Geological Survey of Sweden, 2020b

Abbreviations

AWC	Water holding capacity
Ks	Saturated hydraulic conductivity
BD	Dry bulk density
SOC	Soil organic carbon
SV	Swedish

Figure 7. Flow chart of the method used to combine soil textural and –physical data in order to obtain a complete soil dataset with soil physical properties required for hydrological modelling. From Malmquist and Barron (2023).

Median values of bulk density from Jansson and Karlberg, (2004) were considered for areas of coarse soils (e.g. gravel, bedrock and boulder areas). This was considered feasible due to the similar density of minerals in Sweden (e.g. Knutsson and Morfeldt, 1973; Wallman et al., 2018). Values on water holding capacity and hydraulic conductivity for these soils were extracted from generic coarse soils from CoupModel.

The soil map was joined as a raster, and each pixel was spatially joined with soil depths from the Swedish Soil Depth Model 2020 (Geological Survey of Sweden, 2020) (Figure 7)

4.4.2 Open ditches and natural streams

The most detailed spatial representation of ditches (Lidberg et al., 2021) and stream network available (Ågren and Lidberg. 2020) shows misalignment, i.e. adjacent streams and ditches did not overlap and displayed different flow pathways. Mainly due to the different methods used for producing the two datasets (see Lidberg et al 2021 and Ågren and Lidberg, 2020 for their method description). Therefore, the two datasets, along with manually digitised open ditches from National County Administrative Boards[i] were combined into a continuous dataset that included manually constructed ditches and natural streams. Sections from the stream network from Ågren and Lidberg. (2020) were snapped (i.e. the vertices of one of the vectors align to the other vector's position by moving within a set distance between the two vectors) to the ditch network to spatially line up. Stream segments that overlapped with ditch segments were considered as "true" connectivity. Segments that did not overlap with ditch segments and still overlapped agricultural fields were considered as "false" and omitted as the occurrence of subsurface drainage and soil management tend to erase natural stream pathways from managed agricultural land (Figure 8).

[i] https://ext-geodatakatalog.lansstyrelsen.se/

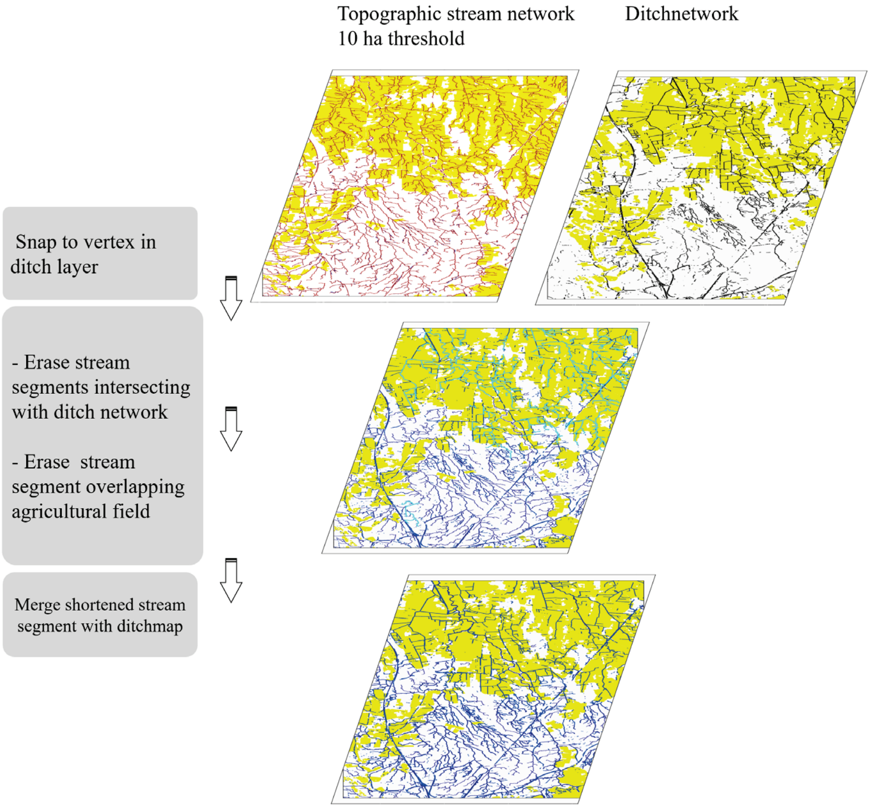


Figure 8. Extraction of improved ditch- and stream data corrected for agricultural land cover, adapted from Malmquist & Barron (2023).

4.4.3 Spatial representation of subsurface drained fields

Subsurface drainage systems are a major characteristic of Swedish agricultural soils. They enhance infiltration capacity and the transport of water through the soil profile. To my knowledge, no large-scale digitised map of subsurface drained fields in Sweden has been created to date. The available maps are either analogue, accessible from County Administrative Boards or, in some cases, digitised and spatially aligned with accurately set coordinates (i.e. georectified) from the Swedish mapping, cadastral and land registration authority (Lantmäteriet). Hence, two different methods were used to create a spatial representation of subsurface drained agricultural fields to depict subsurface drainage systems for hydrological modelling in **Paper II** and **Paper III**.

For the first method, the Economic Map was used as reference. The Economic map is a historic map created 1935-1978 based on an aerial imagery method. The map is a register map of properties, generic land use such as forest, agriculture and urban areas in a scale of 1:10000 (Swedish mapping, cadastral and land registration authority, n.d.). In addition to the original Economic map (henceforth M1), a scanned version (henceforth M2) of the Economic map is available for the former county of Skaraborg (now part of the county Västra Götaland) where agricultural fields with available subsurface drainage plans are marked as diagonal lines over agricultural fields. Map sheets from M2 were georectified to M1. The two maps were classified using a so-called ISO-unsupervised cluster classification (i.e. classification of objects/categories, here land use, in the image layer by colour recognition). Boundaries of agricultural fields were extracted as a separate layer from the other classified land uses and erased from M2, leaving a map with only marked fields with available subsurface drainage plans. Agricultural parcels for 2023 (Swedish Board of Agriculture, 2023) that overlapped with the extracted fields from M1 were marked as subsurface drained. The method was initially limited to the Tidan catchment **(Paper I)** and then extended to the whole of Skaraborg County (Figure 9A).

To extend the representation of subsurface drained fields to the other catchments included in **Paper III,** the method and code from Valayamkunnath et al (2020) was used to create a map of probable subsurface drained fields in southern Sweden. Valayamkunnath et al (2020) used knowledge concerning the extent of agricultural land, subsurface drained area per county, slope and soil drainage class to extract information about probable subsurface drained fields for all of the USA at 30x30m resolution. In order to create a map for arable soils in Sweden, information about subsurface drained areas, agricultural land and slope per county were compiled. Soil drainage classes were categorised based on clay content (Piikki and Söderström, 2019). The code from Valayanathkumar et al., (2020) was adapted to the Swedish maps and a resolution of 50x50m was used to fit the resolution of Åkermarkskartan (Piikki and Söderström, 2019) (Figure 9B). The final map was validated against the dataset from Skaraborg County described above and the final dataset was extracted to use per catchment in **Paper III**.

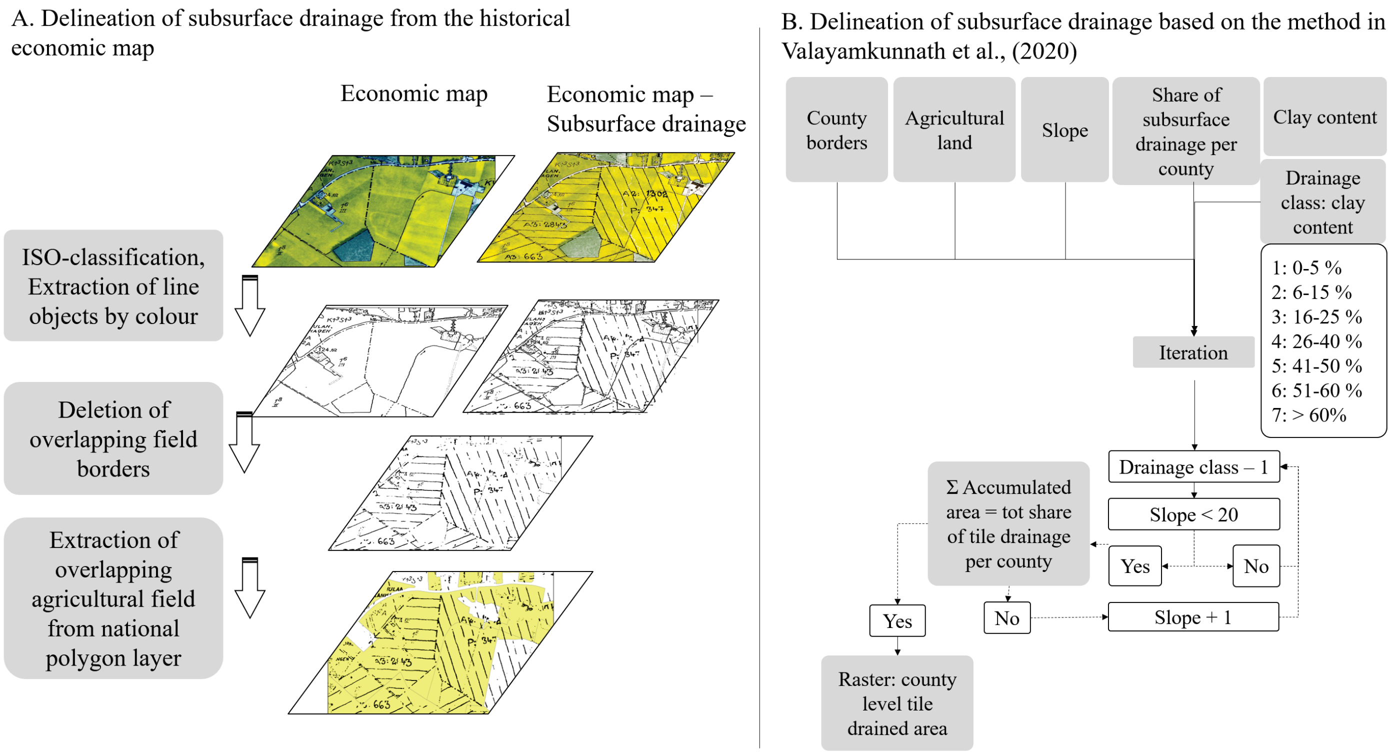


Figure 9. Flow chart over methods for delineating subsurface drainage network from (**A**) the economic map over Skaraborg County and (**B**) for agricultural land in Svealand and Götaland based on the method in Valayamkunnath et al., (2020).

4.5 Outline for hydrological modelling (**Paper II, III**)

4.5.1 Scenario analysis

Paper II, explored the potential effects of restoring historical water bodies on the water balance, given current land use and climate, in order to answer research question II. The Tidan catchment has over the 20th to 21st century experienced a decrease of wetlands by 46 % and increase in lake/pond area by 25 %, the detectable stream-and ditch network from historical and modern maps and databases have increased by 240 % (Lindelöf, 2021; **Paper II**) and the region has overall experienced an expansion of subsurface drainage during the 20th century. Three different scenarios were used based on four different time periods (year 1900-1910, 1955-1965, 2000-2010 and 2010-2020), where the original setting of climate, land use and hydromorphology were modelled. Then changes were done, one-at-a-time, to waterbodies and streams, and climate to introduce historic properties to today's (2010-2020) land use (see Figure 3 in **Paper I**). The models were analysed for changes in the water balance flow variables actual evapotranspiration (ET_a), water yield (the sum of lateral flow, surface run off and tile drainage) and percolation for the Tidan catchment (catchment no. 1 in Figure 5).

In **Paper III,** the effects of climate change on soil moisture and evapotranspiration were explored, to answer to research question III. The included catchments were Tidan, Saxån-Braån, Loftaån-Gamlebyån and Enköpingsån-Örsundaån. The time period 1991-2023 (including the latest 30-year normal period 1991-2020 for climate studies) were compared with climate scenarios derived from the stochastic weather generator Long Ashton Research Station Weather Generator (LARS-WG) (Semenov and Barrow, 1997) based on CMIP6 climate scenarios (Eyring et al. 2016; Pirani et al., 2024). LARS-WG is a semi-parametric weather generator. It was chosen to avoid biases in the precipitation distribution previously observed in downscaled global climate models (e.g. Grusson and Barron, 2022), and to avoid generators that use a predetermined statistical function to produce the weather data (Yin and Chen, 2020). Of the 6 global climate models included in LARS-WG, the model ACCESS-ESM1-5 was used to represent future climate, as this model generated a climate series with the highest change in temperature and precipitation compared to the current climate, to account for potential changes in the anticipated climate change projections.

The future climate was modelled based on two socioeconomic pathways (SSP2-4.5. and SSP5-8.5)[7] which represent the current emission trends, and the worst-case scenario (IPCC, 2023a Fig 2.5; United Nations Environment Programme, 2024, Fig ES.3). This allowed to explore the magnitude of effects potentially required to improve landscape retention capacity to sustain soil moisture under climate change. The climate scenarios were run in two periods from 2024-2040 and the 2041-2060, based on the statistics calculated by LARS-WG.

4.5.2 Agrometeorological indices

Paper III focused on evapotranspiration deficit as an index for crop yield. Furthermore, soil moisture surplus and deficit were explored. The effects of soil moisture and actual evapotranspiration were evaluated based on statistical indices (Soil Moisture Deficiency Index, SMDI and Evapotranspiration Deficiency Index, ETDI) (Narasimhan and Srinivasan 2005), to compare outcomes between catchments.

The ETDI is calculated with Eq. 7 to Eq. 9.

$$WS_{i,j} = \frac{ET_p - ET_a}{ET_p} \qquad \text{Eq. 7}$$

$$WSA_{i,j} = \frac{\overline{WS}_j - WS_{i,j}}{\overline{WS}_j - minWS_j} * 100 \qquad \text{if } WS_{i,j} = \overline{WS}_j$$

$$WSA_{i,j} = \frac{\overline{WS}_j - WS_{i,j}}{maxWS_j - \overline{WS}_j} * 100 \qquad \text{if } WS_{i,j} > \overline{WS}_j \qquad \text{Eq. 8}$$

$$ETDI_j = 0.5 * ETDI_{j-1} + \frac{WSAi,_j}{50} \qquad \text{Eq. 9}$$

[7] Socioeconomic pathways (SSP) are scenarios developed to describe future societal trends of amongst other investment focus, energy resources, policy and lifestyle. The narrative for SSP2 is a pathway without remarkable shifts from historical patterns, with slow shifts towards fulfilling the sustainable development goals. SSP5 is a pathway with increased use of fossil fuels, competitive markets and technological development, with the purpose of increasing the global economy and societal capital (Riahi et al. 2017).

The SSPs are combined with representative concentration pathways (RCP_y) which are time series of varying radiative forcing (y [W m^{-2}]), greenhouse gas emissions and temperature increases. RCP4.5. indicate near term (2031-2050) mean temperature increase of 1.7 °C, while RCP8.5 represent a near term mean temperature increase by 2.0 °C (Gidden et al. 2019; IPCC, 2019, Box SPM.1, p.8).

Where $WS_{i,j}$ is the water stress ratio, ET_p [mm] is the potential reference evapotranspiration, ET_a [mm] is the actual evapotranspiration, $WSA_{i,j}$ [%] is the water stress anomaly, $\overline{WS_j}$ [dimensionless] the long term (1991-2020) median water stress, $maxWS_j$ *and* $minWS_j$ [dimensionless] are the maximum and minimum long term (reference period 1991-2020) water stress, $ETDI_j$ is the Evapotranspiration Deficiency Index, j is the time step and i is the year.

SMDI is calculated as in Eq. 10 and Eq. 11.

$$SD_{i,j} = \frac{SW_{i,j} - \overline{SW}_j}{\overline{SW}_j - minSW_j} * 100 \qquad \text{if } SW_{i,j} = \overline{SW_j}$$

Eq. 10

$$SD_{i,j} = \frac{SW_{i,j} - \overline{SW}_j}{maxSW_j - \overline{SW}_j} * 100 \qquad \text{if } SW_{i,j} > \overline{SW_j}$$

$$SMDI_j = 0.5 * SMDI_{j-1} + \frac{SD_j}{50}$$

Eq. 11

In Eq. 10, $SD_{i,j}$ [%] is the soil moisture deficit [%], $SW_{i,j}$ [mm] is the mean soil moisture per time step j, $\overline{SW_j}$:[mm] is the long term (1991-2020) median soil moisture content, $maxSWj$ [mm] is the maximum and $minSWj$ [mm] the minimum long term (1991-2020) soil moisture, j is the time step and i is the year. Lastly, $SMDI_j$ is the soil moisture deficiency index.

The indices SMDI and ETDI varies between -4 and +4, where negative values indicate dry conditions and positive values wet conditions.

These indices were related to the meteorological indices Standardised Precipitation Index (SPI) (WMO, 2012) (Eq. 12) and the temperature index for warm days, TX90p (Zwiers and Zhang, 2009) (Eq. 13).

$$SPI = \frac{(P_i - \bar{P})}{\sigma}$$

Eq. 12

$$TX90_p = \frac{N(TX_{i,j} > TX90)}{N} * 100$$

Eq. 13

The variable P_i is the precipitation per time step i, $\bar{P}i$ is the long term mean precipitation (1991-2020), σ is the standard deviation. SPI ranges between -3 to +3, where positive values of SPI indicate wet conditions (SPI > 2 is extremely wet) and negative values indicate dry conditions (< -2 is extremely dry).

For the temperature index TX90p [%], the variable $TX_{i,j}$ is the maximum temperature for time step i, The evapotranspiration deficiency index (ETDI) was modelled at monthly time step, while absolute soil moisture and SMDI, SPI and TX90p were calculated on weekly time step. The effects of of soil moisture were explored by two layers (SMDI2 = 10-20 cm and SMDI6 = 50-60 cm) to explore risk of early onset drought for seedlings during early root development and during later crop growth stages). All indices were calculated in RStudio (version 2023.03.0 build 386, R Studio Team, 2023).

In addition, the anomalies were compared with absolute values defined as extreme shown to be hazardous for crop production in the literature (Table 2). These absolute thresholds were selected based on their capacity to describe the impact on crop yield through surplus/deficit of water availability for crop water supply and limitations to field operations.

Table 2. Absolute soil moisture and evapotranspiration thresholds with negative implications for crop yield and field operations used to classify extreme soil moisture and evapotranspiration situations from climate scenarios modelled with Soil and Water Assessment Tool (SWAT+)

Threshold	Index	Index classification	Reference
Soil moisture	Soil saturation threshold hazardous for crop yield – lodging event Days exceeding wet limit for tillage	≥ 0.9 of pore water volume*	Malik et al., 2002; Trnka et al., 2014; Obour et al. 2019
	Soil water content inhibiting field operations	θ range < 10% or > 70%.of maximum soil water holding capacity	Trnka et al. 2011
Evapo-transpiration	Water deficit during growing season	Days when ETa/ETp < 0.4	Trnka et al., 2011

4.5.3 Sensitivity analysis, calibration and validation

Sensitivity analysis, calibration and validation were done in the R-software RSWAT (Nguyen, 2007). Calibration and validation were done for monthly streamflow and ET_a (Running et al., 2021, 2017). For **Paper III**, water balance parameters were initially constrained by soft calibration. Flow peaks and ET_a were adjusted by hard calibration (**Paper II** and **Paper III)**. Validation on the magnitude of modelled crop yield compared to observed, was additionally done in **Paper II** (Swedish Board of Agriculture, 2023). The model representation was evaluated by the objective functions[8] aBIAS for **Paper II** and PBIAS for **Paper III** and KGE, R^2 and visual inspection (**Paper II** and **Paper III**).

Calibration in **Paper II** was done for 2010-2016 and validation for 2017-2020 based on observed streamflow (one station) and actual evapotranspiration (aggregated to monthly level from MODIS (MOD26A) (Running et al., 2017). In **Paper III,** the full time series of observed streamflow (two to four gauges per catchment) were used for calibration (the years available for calibration varied between catchments and stream gauges). Calibration and validation periods for actual evapotranspiration (MODIS, MOD16A v006 and v061) (Running et al., 2021, 2017) were selected to include periods of both higher and lower precipitation and temperature compared to normal values over the period 1991-2023.

4.5.4 Statistical analysis

Variations in the distribution of temperature and precipitation between the historical and current climate (**Paper II**), were evaluated by using the non-parametric Wilcoxon Signed Rank Sum test (Wilcoxon, 1945). This test assesses differences in distribution between two dependent tests while avoiding prior postulation on the individual distributions. Variation in soil moisture conditions, evapotranspiration, precipitation and temperature in **Paper III** were explored with the Seasonal Mann Kendall test corrected for autocorrelation (Kendall, 1975; Mann, 1945). Correlations between indices

[8] Objective functions are mathematical functions that evaluate the fit of modelled data against observed data in validation. There are many different objective functions which capture different representability of the modelled data, e.g. peak values, low values, mean trends or distributions. The choice of objective function or more for multiobjective function evaluation is determined on the importance of the study to capture certain signatures in the observed variable(s).

were evaluated with the Spearman correlation (Spearman, 1904) test for indices SMDI, ETDI, SPI, and TX90p.

5. Results

5.1 Increased resolution of spatial data representing flow pathways, water storage and retention potential (**Paper I**)

5.1.1 Soil physical properties

Soil moisture is impacted by spatial and temporal variations in soil physical properties governing infiltration and water retention. To explore water balance changes in agriculturally dominated catchments (**Paper II** and **Paper III),** development of indata describing landscape soil properties and water infrastructure was needed to represent current and historic conditions of an agricultural landscape. Two different soil classification systems were used to create soil texture maps and linked soil physical properties per soil class, FAO-textural classification henceforth referred to as FAOsoil, and Swedish soil classes, henceforth mentioned as SWsoil.

Using the two soil classification systems affected the area assigned to different infiltration classification properties, represented by saturated hydraulic conductivity (K_s), water holding capacity (AWC) and drainage. Firstly, the number of soil profiles included using FAOsoil (n=35) was lower than classification in SWsoil (n=45). This was caused by a lumping of soil classes in the FAO-system compared to the Swedish system. The difference in soil textural classes impacted the assigned K_s and AWC. FAOsoil classification resulted in a larger area of moderate to very rapid K_s (34 % and 21 % respectively of the catchment area) compared to SWsoil, where the largest area had K_s values representing moderately slow and very rapid soil water flow (44% and 29% respectively of the catchment area). Water holding capacity varied mainly between 20-40 mm per 10cm^{-1} for SWsoil (82% of the catchment area) and below 40 mm per 10 cm^{-1} in FAOsoil (94 % of the catchment area) (Table 3). Bulk density was higher in SWsoil dataset (1.2-1.8 g cm^{-3}) compared to FAOsoil (0.8-1.6 g cm^{-3}) for the topsoil (0-10 cm). For values for the subsoil and absolute values, see **Paper I.** The soil classification system greatly impacted the representation of infiltration and water storage, with higher K_s and lower AWC when changing from FAO soil data set to SWsoil dataset for the catchment.

Table 3. Summary table on water component data, extracted from **Paper I**. The acronym Ksat is the saturated hydraulic conductivity, and AWC is the water-holding capacity of soils. The values represent the topsoil 0-10 cm.

Variable		**Paper I**		**Difference**
		Soil set 1 (FAOsoil)	**Soil set 2 (SWsoil)**	
No. of soil profiles (n =)		35	45	10
K_s [mm h^{-1}] (% of land area, topsoil 0-10 cm)	Very slow	10	10	0
	Slow	0	2	2
	Moderately slow	44	14	-30
	Moderate	13	34	21
	Moderately rapid	3	3	0
	Rapid	1	16	15
	Very rapid	29	21	-8
AWC [mm 10 cm^{-1}] (% of land area, topsoil 0-10 cm)	0-20	9	31	22
	20-40	82	63	-19
	40-60	4	2	-2
	60-80	4	4	0
	80-100	0	0	0
Dry bulk density [g cm^{-3}] (% of land area, topsoil 0-10 cm)	0.2-0.4	7	0	-7
	0.4-0.6	3	1	-2
	0.6-0.8	0	0	0
	0.8-1.0	13	13	0
	1.0-1.2	6	10	4
	1.2-1.4	44	37	-7
	1.4-1.6	9	34	25
	1.6-1.8	17	4	-13
	1.8-2.0	0	0	0

5.1.2 Open ditches and stream network

The extent of water flow pathways, storage facilities, and diversion through natural and manmade structures are important parameters affecting the water cycle (Abbot, 2019b). Yet spatial resolution can be a challenge for portraying relevant structures, as subsurface drainage of agricultural fields has erased flow pathways that would naturally occur due to topographic variation. Hence, natural water flow pathways (i.e. hydromorphology) are sometimes substantially modified at the local scale. Here, three datasets were used to develop a more representative network of manmade ditches and natural streams to describe the current flow pathways in an agricultural landscape. The combined ditch and stream dataset developed in **Paper I** had a significant impact on the water infrastructure in the Tidan catchment. It increased the length of surface water pathways compared to the individual input datasets. After erasing overlapping stream segments and erasing “false streams”, the total length equalled 5350 km for the Tidan catchment (Table 4). Of the topographic stream network, 2470 km did not intersect with the ditch network, which was therefore defined as false (see section 4.3.2) and subsequently erased to create the final map. The new stream length consisting of manmade ditches and natural streams was significantly increased compared to the individual datasets (Table 4)

Table 4. Summary table on difference in length of improved combined stream- and ditch network compared to the original datasets.

Reference	**Total length [km]**	**Difference to the new dataset**
Paper I: Stream and ditch network	5350	
Ågren and Lidberg (2020)	4701	-649
Lidberg et al. (2021)	2423	-2927
County Administrative Board of Västra Götaland (2021)	774	-4576

5.1.3 Subsurface drainage

To spatially include (manmade) subsurface drainage systems in the water balance, maps over subsurface drainage were based on two methods. Subsurface drained fields were extracted from the Economic map of the Tidan catchment and 69% of the agricultural fields were defined as drained. This was comparable to statistics of subsurface drained field area for the County of Västra Götaland (64%, Swedish Board of Agriculture, 2017).

A second method applied in the USA, based on classes of drainage capacity of the soils and slope (Valayamkunnath et al., 2020) was used to create a subsurface drainage map for other counties and the catchments in

Paper III. This method combined county statistics to guide the extraction of subsurface drained pixels. A comparison of the national subsurface drainage map extracted from fields from the economic map in Skaraborg showed good agreement (overall accuracy = 0.8, kappa = 0.5) between the two maps (Figure 10). This indicates that the representation of area covered by subsurface drainage by county is representable, but it needs further validation from independent ground truth data from other subsurface drained agricultural fields.

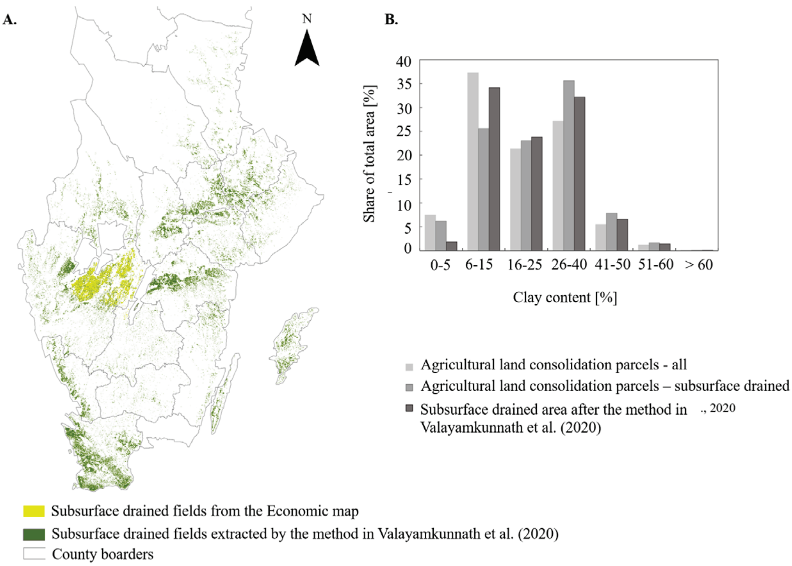


Figure 10. Subsurface drained field extracted from the Economic map (yellow) and by the method in Valayamkunnath et al. (2020) based on county statistics of subsurface drained area (A). (B) shows the share of area under subsurface drainage per clay content class and method.

5.2 Calibration and validation of baseline models (**Paper II** and **Paper III**)

To explore the catchment scale water balance components for past, current and future climate, in catchments with various levels of water infrastructure, the SWAT+ model was used (**Paper II** and **III**).

Paper II was calibrated for 2010-2016 and validated for 2017-2020, using observed stream flow and ET_a. The model agreement for **Paper II** was better between observed and modelled values for the calibration period than the validation period. Streamflow was underestimated during the calibration period and overestimated during the validation period. Validation of ETa showed larger variation (aBIAS = 37.1), yet the overall fit was reasonable (KGE = 0.41). Validation against crop yield showed a correlation with and R^2 of 0.54 (Table 5). The calibrated model in **Paper II** underestimated high flows and overestimated low flows in the first half of the calibration period (2010-2013). In the second half of the calibration period (2014-2016) and during the validation, flow peaks were overestimated and low flows had a better fit to observed values.

The calibration for **Paper III** showed less agreement with a good threshold for the selected objective functions (Gupta et al., 2009; Moriasi et al., 2007). Overall, the models underestimated monthly high flows during winter and spring, while streamflow from April to September agreed with observed stream flow in a visual analysis. However, the objective functions still showed lower values than what would be considered a suitable fit. Overall, values for ET_a, were underestimated for Tidan, while ET_a was overestimated for Enköpingaån-Örsundaån, Loftaån-Gamlebyån and Saxån-Braån. The over and underestimation of ETa increased with increasing observed values (Table 5). However, as the modelled values for **Paper III** still follow the annual fluctuations, though with lower magnitudinal variation, the results are presented as an indication of a potential future change in magnitude.

Table 5. Values of the objective functions Kling-Gupta Efficiency (KGE), Absolute Bias (aBIAS), Percent Bias (PBIAS) and Coefficient of Determination (R^2) during calibration and validation of models set up with the Soil and Water Assessment Tool (SWAT+) for the Tidan catchment (**Paper I** and **Paper III**) and Loftaån-Gamlebyån, Saxån-Braån and Enköpingsån-Örsundaån catchments (**Paper III**). Calibration was done using actual evapotranpsioration (ET_a) while validation was done for both discharge (Q) and ET_a.

Model		**Catchment**	**Parameter**	**Objective function**			
				KGE	aBIAS	PBIAS	R^2
Paper I	Calibration	Tidan	Q	0.47	20.5		0.32
	Validation		Q	0.59	-4.78		0.64
	Calibration		ETa	0.47	37.1		0.41
	Validation		ETa		20.5		0.32
Paper III	Calibration	Loftaån-Gamlebyån	Q	0.36		48.6	0.61
		Saxån-Braån	Q	-0.23		74.1	0.29
		Tidan	Q	0.07		51.4	0.24
		Enköpingsån-Örsundaån	Q	-0.35		69.5	0.15
	Calibration	Loftaån-Gamlebyån	ETa	0.53		12.4	0.72
		Saxån-Braån	ETa	0.42		35.5	0.70
		Tidan	ETa	0.58		-23.9	0.74
		Enköpingsån-Örsdundaån	ETa	0.52		5.1	0.50
	Validation	Loftaån-Gamlebyån	ETa	0.55		10.9	0.75
		Saxån-Braån	ETa	0.71		17.1	0.72
		Tidan	ETa	0.53		-27.2	0.74
		Enköpingsån-Örsdundaån	ETa	0.54		6.6	0.52

5.3 Effects of historical climate and land use change on water balance (**Paper II**)

5.3.1 Climate change in historical scenarios

Four 10-year periods from 1900 to 2020 (i.e. 1900-1910, 1955-1965, 2020-2010 and 2010-2020) were modelled in **paper II** to represent various degrees of agricultural intensification. The maximum temperature (T_{max}) for 1900-1910 and 1955-1965 as well as the minimum temperature (Tmin) for 1900-1910, 1955-1965 and 2000-2010 were significantly lower ($p < 0.05$) in comparison to 2010-2020. The average maximum temperature in 1900-1910 was $\overline{T}_{max}$= 9.3 °C and 1955-1965 it was $\overline{T}_{max}$ = 9.0 °C. Furthermore, the standard deviation (SD) decreased for each time period with an overall decrease from 1900-1910 to 2010-2020 from 5.7 °C to 2.1 °C. This could partly be an artefact from changes in measurement equipment, change of location and method since early years' measurements (e.g. Bergström & Moberg 2002; Moberg et al. 2002). Comparing precipitation between the historical scenarios by Wilcoxon rank sum test did not disclose any significant differences between the time periods (Figure 11). However, the difference in annual precipitation of +105 mm yr^{-1} from 1900-1910 to 2010-2020. Hence, the precipitation increase to current time is consistent with overall observed precipitation increase, yet the overall increase of precipitation on national scale over the century have shown to be significant (Schimanke et al., 2022, Section 3.6.1).

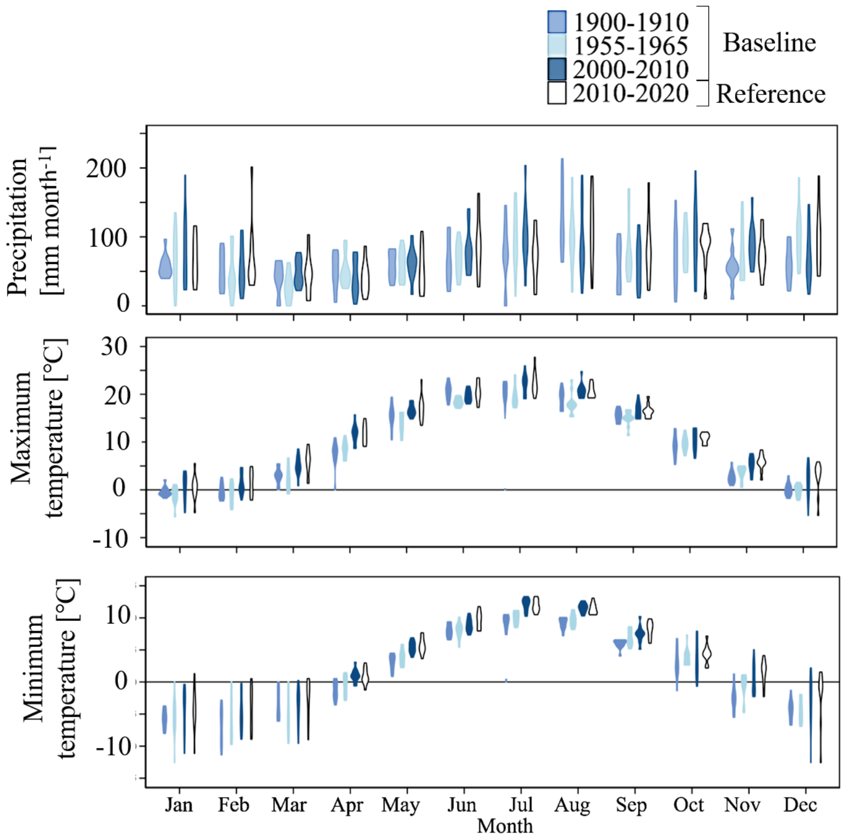


Figure 11. Observed average maximum and minimum temperature and monthly average precipitation for the historic reference periods (1900-1910, 1955-1965 and 2020-2010) and the baseline period 2010-2020 modelled in **Paper II**.

5.3.2 Effects of historical landscape features as water retention measures (**Paper II**)

Comparing the SWAT+ modelled water balance for different hydromorphology in historical agricultural landscapes before and after implementation of subsurface drainage, proved difficult due to limitations in temporal and spatial resolution in the historical land use, management practices and coverage of waterbodies. Significant differences were obtained in actual evapotranspiration, water yield and percolation, especially comparing 1900-1910 to 2010-2020. The modelled water balance comparing historical land use, hydromorphological landscape and weather with present time (2010-2020) revealed significant ($p < 0.05$) increase in water yield (the sum of surface runoff, lateral flow and subsurface drainage) and percolation compared to the 1900-1910 pre-drained landscape state. Seasonal significant differences were found for percolation (between -72 % to -96 % (corresponding to -15 to -7 mm mon^{-1}) during autumn-winter, while water yield only were significantly different (-57 %, corresponding to -14 mm mon^{-1}) in November. The average actual evapotranspiration was overall lower for all three historical water balances on annual basis yet only significantly lower in 1955-1965 (-9 %, corresponding to -47 mm). On monthly level however, significant differences occurred for 1900-1910 (April, Augusti, September) (- 8 % to +19 %, equivalent to -9 to + 8 mm mon-1) and 1965-1955 (March-June, November-December) (-20 % to -8 %, equivalent to -13 to -1 mm).

Including the area of wetlands, waterbodies and stream/ditch-network from historical maps in current landscape and climate of the Tidan catchment, did not result in any significant differences compared to current land use and extent of water bodies. However, an absolute difference was noted in increased wateryield, especially in the scenarios with the least coverage of wetlands (from +2 to +21 % corresponding to +6 to +85 mm mon^{-1}).

The major difference between the historical scenarios were affected by changes in temperature and potentially accumulated difference in precipitation, especially for the periods 1900-1910 and 1955-1965, shown by similar difference in ET_a and percolation, both for average values and standard deviation as the baseline historical scenarios. However, for wateryield, the historic climate variables under current land use and hydromorphology indicated larger decrease for water yield than the baseline scenarios. Hence, a higher area of wetlands seem to decrease the wateryield on average. The lower variation between current hydromorphological landscape and including historic wetlands and hydromorhology might be due to the interchange of reduced wetlands on one hand in today's landscape and a more complex stream network on the other.

These results modelling the water balance in the Tidan catchment for various levels of manmade water infrastructure changes in historic and current landscape, oppose results from previous studies showing that land use change, rather than weather change has had a larger effect on ET_a (Section 3.6).

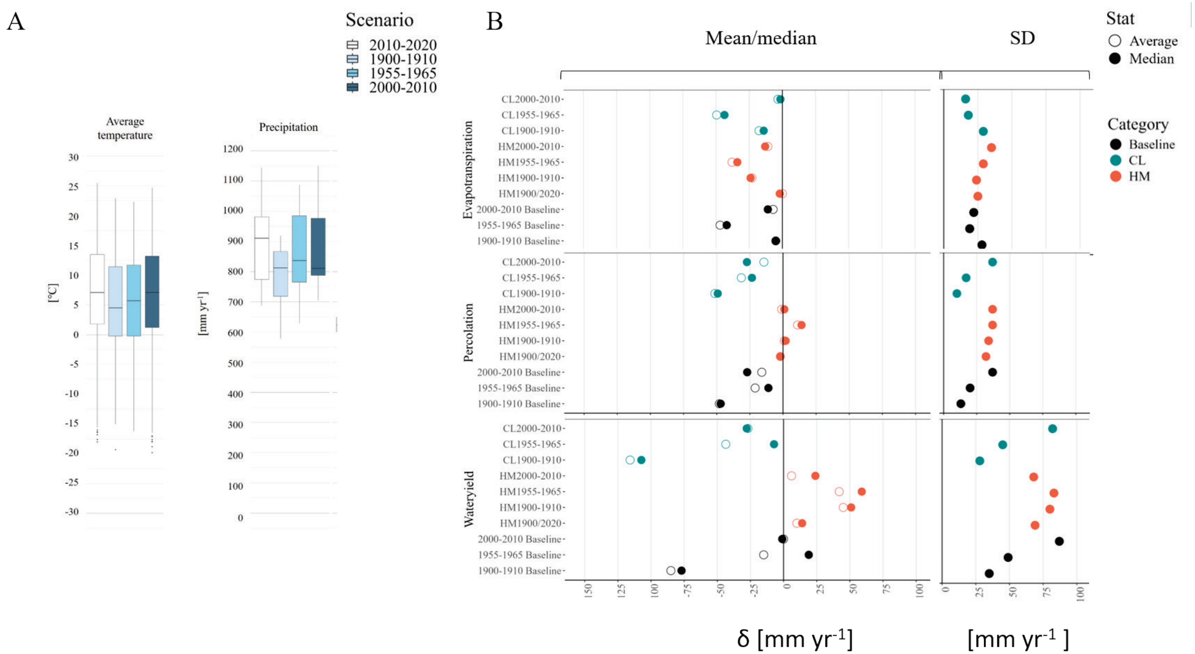


Figure 12. **(A)** Temperature and precipitation over the 10 yr periods 1900-1910, 1955-1965, 2000-2010 and 2010-2020. and **(B)** absolute difference and standard deviation of actual evapotranspiration, water yield (sum of surface runoff, lateral flow and drainage) and percolation at basin level for historical baseline scenarios (climate, hydromorphology, waterbodies and land use per individual decade), hydromorphological scenario (HM: landuse and climate for 2010-2020 but with hydromorphology from respective historic decade), climate scenario (CL, land use and hydromorphology for 2010-2020 but climate from respective historic decade) and the standard deviation per respective water flow pathway.

5.4 Change in soil moisture under climate change (**Paper III**)

Given the importance of soil moisture in the water balance for production in agricultural landscapes, **Paper III** explored the soil moisture resilience at 0-60 cm depth, representing the principal root zone, towards extreme events to complement the historical catchment study with land use and hydro morphological changes (**Paper II**). The study represents the diverse climatic and hydrological agricultural landscapes in southern Sweden, where rainfall decreases from west to east. The results are the outcome from the hydrological model SWAT+.

5.4.1 Climate change in generated weather series for future scenarios

The weather generator LARS-WG was used to develop representative future climate as weather input data series (Section 4.5.1). The highest increase in monthly average maximum (minimum) temperature for the generated climate scenarios (SSP2-4.5 and SSP5-8.5) (**Paper III**) occurred for Tidan and the least for Saxån-Braån (Figure 13).

The average precipitation volume per precipitation event varied between -2 to + 3 mm per rain day, comparing the reference period 1991-2023 and future scenarios. The reduction in precipitation compared to the reference period was lower in during May to September compared to the other months. An increased precipitation was in contrast observed during September-March for all catchments. The inter-annual variation of standard deviation followed the variation of average daily precipitation, varying between -2.5 to + 1.8 mm per rain day, with increased fluctuations between months and increased warming scenario (Figure 14).

The difference in the average precipitation days compared to 1991-2023 changed between -2 to +1 day, except for Saxån-Braån where the future scenarios indicated a difference of -2 to +3 precipitation days per average, SD varied between – 4 and +3 days.

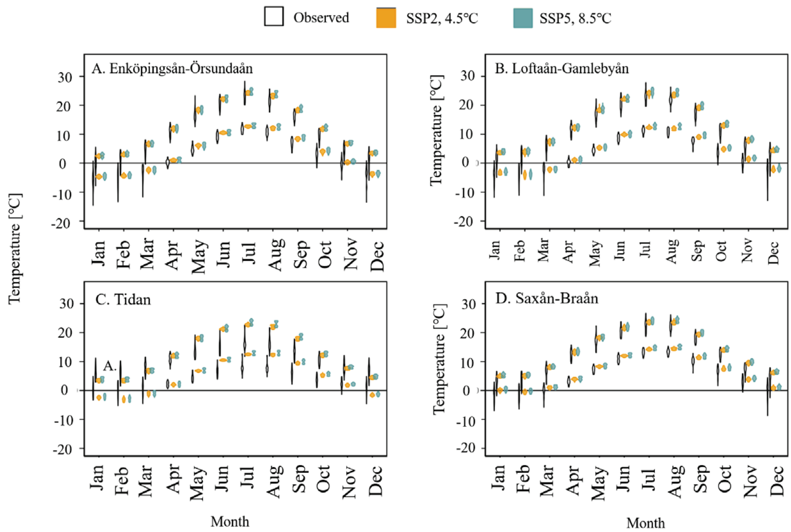


Figure 13. Average monthly maximum and minimum temperature for the reference time period and future climate scenarios modelled in **Paper III,** Enköpingsån-Örsundaån (A), Loftaån-Gamlebyån (B), Tidan (C) and Saxån-Braån (D). The future scenarios (SSP4,-2.5 and SSP5-8.5) were generated with the weather generator LarsWG.

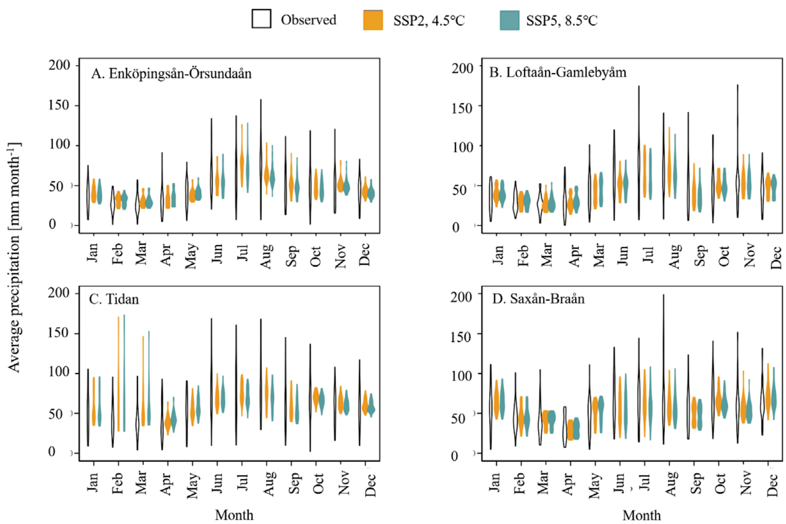


Figure 14. Average monthly precipitation for the reference time period and future climate scenarios modelled in **Paper III**, Enköpingsån-Örsundaån (A), Loftaån-Gamlebyån (B), Tidan (C) and Saxån-Braån (D). The future scenarios (SSP4-2.5 and SSP5-8.5) were generated with the weather generator LarsWG

Considering changes in extreme precipitation patterns, the number of precipitation days was similar for the future scenarios compared to the reference period, yet with an overall narrowing of the distribution with an increased number of dry days and a decreased number of wet days (±3 days for the driest 10th percentile with the largest difference in April, June and August). For the wet 90th percentile the largest increase (+ 3 days) occurred in May in Saxån Braån, and the least in Saxån-Braån and Loftaån-Gamlebyån during April, May and August (-2 days).

The precipitation volume per day with precipitation for the wettest 90th percentile decreased more in the latter time scenario, and more in SSP5-8.5 than SSP2-4.5. The largest increase occurred in Loftaån-Gamlebyån, (May, +2 mm per day with precipitation, SSP 2-4.5). The largest decrease occurred in August and September (-5 to -4 mm per day with precipitation, SSP5-8.5) for Saxån-Braån and Tidan. The driest 10th percentile did not indicate any difference (Figure 4, **Paper III**).

5.4.2 Change in soil moisture under climate change

The study in **Paper III** used four indicators of actual evapotranspiration, soil moisture, precipitation and temperature. The soil moisture deficiency index (SMDI) was explored in two soil layers (SMDI2 = 10-20cm and SMDI6 = 50-60 cm) (Section 4.5.2). All trends are presented related to the reference period 1991-2023 unless stated otherwise, where significant, referring to $p > 0.05$.

During the cropping season (April to September), the results showed a significant trend of reduced ET_a with increased warming scenario for all four catchments. The trend started earlier during the cropping season the further northward location of the catchment.

The SMDI indicated a drying trend in soil moisture for all four catchments in the subsoil (50-60 cm, SMDI6) and in the topsoil (10-20 cm, SMDI2) for three out of four catchments during July-August. The trend showed longer periods of significant drying in the subsoil and increased difference with increased warming (darker red in Figure 15 and Figure 16). The northern most catchment Enköpingsån-Örsundaån indicated a different pattern, yet non-significant for the major part of the cropping season, except for the start of August, for the topsoil. The conditions were drier in the start of the cropping season and wetter towards the end (Figure 15, Figure 16).

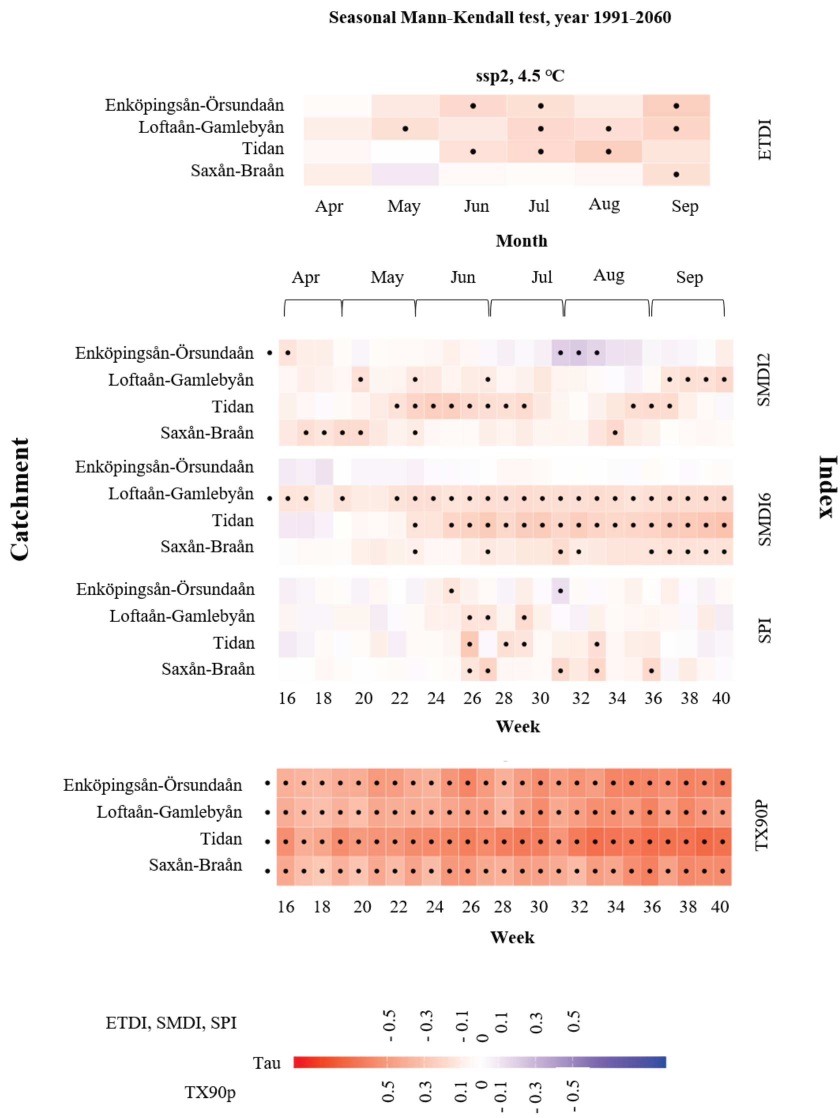


Figure 15. Results obtained with climate scenario CMIP6, SSP2-4.5, **Paper III**. Tau (colour) and significance trend of the indices Evapotranspiration Deficiency Index (ETDI), soil moisture deficiency index for topsoil (SMDI2) and subsoil (SMDI6), Standardised Precipitation Index (SPI) and the share of days exceeding 90th maximum temperature threshold (TX90p) according to the seasonal Mann-Kendall test where the black dots represent significant trends ($p < 0.05$) for the catchments Enköpingsån-Örsundaån, Loftaån-Gamlebyån, Tidan and Saxån-Braån. Tau shows the monotony of the trend slope and varies between -1 and 1 where a positive value indicate an increasing trend. Note the reverse scale for the index TX90p.

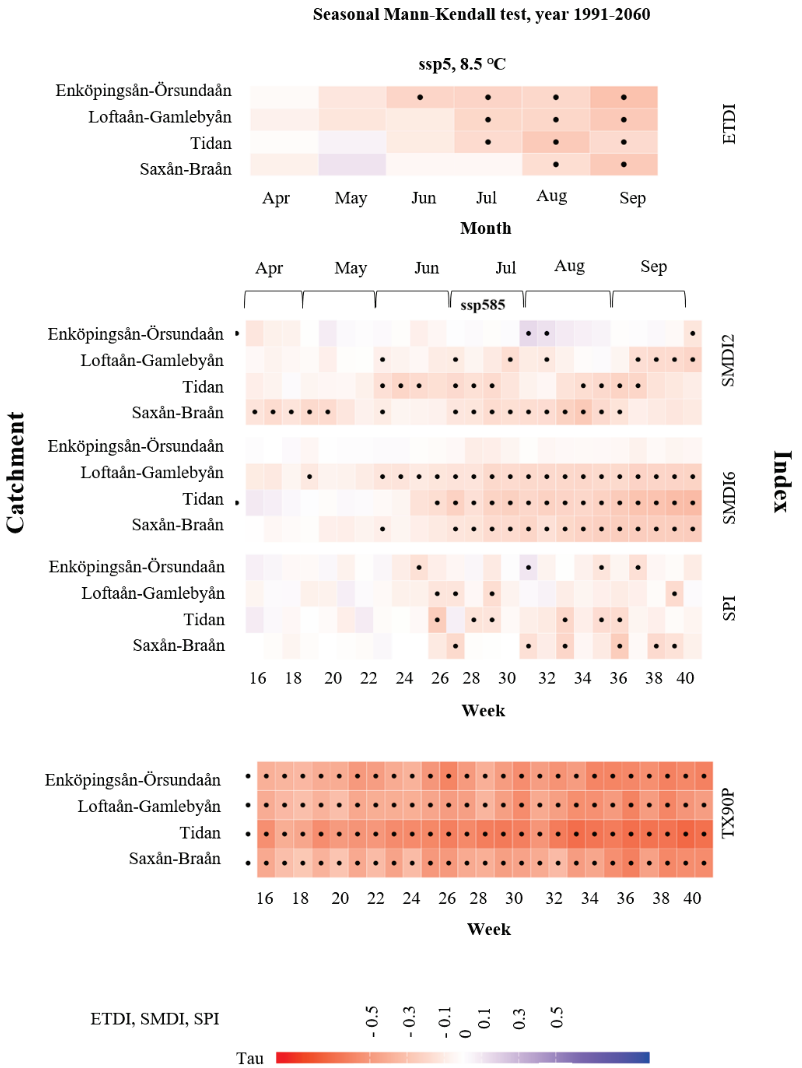


Figure 16. Results obtained with climate scenario CMIP6, SSP5-8.5, **Paper III**. Tau (colour) and significance trend of the indices Evapotranspiration Deficiency Index (ETDI), soil moisture deficiency index for topsoil (SMDI2) and subsoil (SMDI6), Standardised Precipitation Index (SPI) and the share of days exceeding 90th maximum temperature threshold (TX90p) according to the seasonal Mann-Kendall test where the black dots represent significant trends ($p < 0.05$) for the catchments Enköpingsån-Örsundaån, Loftaån-Gamlebyån, Tidan and Saxån-Braån. Tau shows the monotony of the trend slope and varies between -1 and 1 where a positive value indicate an increasing trend. Note the reverse scale for the index TX90p.

The trend in ETDI and SMDI6 showed a similar drying trend for the respective catchments, despite no significant shift in precipitation with increased emission scenario. The SPI only indicated significant less precipitation in June and July, also confirmed by the modest increase in precipitation volumes for the climate series shown in Section 5.3.1). Hence our results could not be explained by solely reduced precipitation. The important insight from these results is that dry conditions prevail throughout the crop season even though rainfall did not change.

The aim was to explore the link between extreme precipitation by the Standardised Precipitation Index (SPI) on the one hand, and extreme temperature defined by the 90th percentile of maximum temperature (TX90p) on the other. Surprisingly, no clear significant correlations over the season between the meteorological indices explaining the decreasing trends in SMDI and ETDI where obtained. However, June and July indicated significant trends during the reference period 1991-2023 with mainly for Loftaån-Gamlebyån between SMDI2 (SMDI for the topsoil) and TX90p (negative correlation) and a positive correlation to SPI during the current- and previous week (see **Paper III**, Figure 8).

Exploring shifts in absolute soil moisture saturation ($\theta_t > 0.9\ \theta_{FC}$), where θ_{FC} is the soil moisture at field capacity and θ the soil moisture at time step t, did not show a major difference over the climate scenarios (within ±1 % (topsoil) and ±5 % (subsoil) difference compared to the reference period) and low area prone to flooding overall compared to dry areas. Hence, this confirms a drying trend toward the end of the crop season in three out of four catchments.. The response was stronger in the subsoil compared to the topsoil, which is consistent with the results based on indices.

Surprisingly, an inspection of the percent land area with soil moisture content below the wilting point ($\theta_t < \theta_{WP}$), indicated a consistent pattern over time, with less dry area in the subsoil at the start and increasing dry area at the end of the crop season for Enköpingsån-Örsundaån catchment and the Tidan catchment . The same trend was obtained for the Saxån-Braån catchment, yet with higher percentage change. For the topsoil, the increase in area with soil moisture content below the wilting point ($\theta_t < \theta_{WP}$) was largest for Enköpingsån-Örsundaån (both climate scenarios) and Saxån-Braån (SSP5-8.5). It was noticeable that the two eastern catchments, Enköpingsån-Örsundaån and Loftaån-Gamlebyån, showed a lower change in percentage area where $\theta_t < \theta_{WP}$, while the Tidan and Saxån-Braån, that lies further to the west, showed a larger absolute change overall.

Furthermore, while the variation between years seemed consistent for future climate, the main variation between years was shown for Saxån-Braån, while the other three catchments overall indicated low variation. The results are surprising due to that the precipitation volume indicated reduced variability and just few days change in precipitation occurrences. Additionally while a clear temperature increase was noted, the temperature ranges does not show a major increase of temperatures above defined thresholds for potential crop damage (e.g. Trnka et al., 2011; Trnka et al., 2014). Hence, while **Paper III** showed an increasing drying trend of soil moisture and evapotranspiration over time, the absence of correlation between selected weather indices suggest further exploration of weather-related linkages.

6. Discussion

6.1 Improved spatial description of soil and hydrological pathways and agricultural, hydrological landscape properties

Based on previously published datasets, three new datasets were developed, with higher spatial resolution and coverage for the agricultural catchment Tidan, in south-eastern Sweden (**Paper I**). The first data set consisted of a map of soil physical properties linked to soil texture, including hydraulic conductivity and water holding capacity for both forest and agricultural land. Secondly, stream-ditch network and subsurface drainage spatial representation were developed that better reflect the location of manmade open ditches and subsurface ditches over agricultural land. Thirdly, historic and current wetlands were mapped to understand landscape retentions losses and gains over the period 1900 to 2020. With these improved descriptions, water flows and storage changed considerably from previous data, and importantly, better reflect the anthropogenic modifications to flows and storage in agricultural landscape.

Including tile drainage as a measure in hydrological models has been shown to be important to improve the results (e.g. White et al. 2024). Here, an approach to spatially determine the location of tile-drained fields was used. While they still need further validation, e.g. by combining deep learning models/artificial intelligence and satellite imagery (e.g. Carlsen et al. 2024), or via locally digitised tile drainage maps (e.g.Land: Lantbruk, Skogsbruk 2023), as of now, the map provides an addition for including in spatial analysis of, e.g., flood risk areas, and hydrological models.

Improvement of physical-based hydrological models (e.g. Jarvis et al., 2022) demand representable physical indata for sufficient resolution for reliable interpretation of the results. It is recognised that collecting and analysing observation data is labour intensive and costly. It can also be challenging to scale up point samples to a larger scale in a meaningful way (Rinderer and Siebert, 2012).

The spatial description might become more important to properly use more complex gridded models that maintain the spatial location of parameters and objects, which was used in the analysis in **Paper I**. A common alternative is the compiling landscape properties into lumped, e.g.

hydrological landscape units (HRUs) or objects of similar property. Such approach reduce the possibility of the spatial evaluation of cause-effect e.g. flood events, or evaluation of location of specific measures aimed at water retention.

Spatial scale is a fundamental challenge in hydrological, environmental, and ecological modelling and can have a significant impact on the output (e.g. Blöschl & Sivapalan 1995). The influence of land use change and climate change overlap over catchment scale especially related to floods. For example, influence of land use tend to increase in heterogeneity over larger scale and response to small storms decrease over scale while flooding on large catchment scale tend to be dominated by regional, more long term storms due to saturation excess (Blöschl 2022).

While the datasets developed in **Paper I** have potential use in spatial GIS-analysis and hydrological modelling, three parameters for exploring water balance are still in need for further development. First, potential irrigation is one crucial parameter when discussing water balance under alteration climate conditions in agriculture. It has previously been a parameter that improve representation in the water balance also in boreal temperate catchments (Strömqvist et al. 2020). Yet, the spatial- and temporal representation of irrigation occurrence and irrigation water outtake in Swedish conditions is not collected as national datasets, and inclusion on catchment scale is dependent on assumptions. Secondly, to improve the spatial representation of surface water flow pathways in **Paper I**, the representation could have been improved with knowledge of true location of underground flow pathways such as culverts as well as built up areas and landscape recharge-discharge patterns especially related to wetlands.. ()

6.2 Estimates of historical water balance and potential consequences for understanding historical water retention

Using historical maps representing four different decades during the 20th century (**Paper II**), the current and historical water balances were explored to understand the effects of historical and current waterbodies and streams networks for different weather conditions. The aim was to provide insight into the discussions of rewetting historic wetlands and highlighted focus on nature-based solutions as a complement to traditional engineered solutions for water retention at the landscape level (**Paper II**). The results from modelling catchment water balances with SWAT+ showed a small but significant ($p < 0.05$) decrease in percolation and decrease in catchment water yield between 1900-1910 and 2010-2020. There was a variation between positive and negative change for ET_a during all months and percolation (-7 to 15 mm $month^{-1}$) in the first yearly quarter between 1900-1910 and 2010-2020 for the southwestern mesoscale catchment of Tidan, that had a reduction of wetlands of 46 % over the period. It was possible to ascribe the hydrological changes mainly to weather changes, mainly the temperature, rather than in land use and hydromorphology (described as primarily a change of area and land location of wetlands between time periods). Changes in percolation and evapotranspiration were predicted in the same magnitude and direction when running the model with the present land use and hydromorphology but with the historic climate of the three different time periods, although non-significant. The average water yield was higher with lower wetland area and increased stream length, yet with maintained standard deviation, potentially reflecting the lower water storage capacity with lower wetland area and stream reaches.

The results of modelling historic and current water balance in an agriculturally modified landscape could be interpreted carefully as a possible opportunity for the expansion of water infrastructure measures in the arable landscape. However, the absolute amount (in space and flow-storage infrastructure, whether nature-based or engineered) is difficult to assess. This leads to challenges in determining restoration goals of historical water balance and functions in a landscape that is interfered by anthropogenic interventions, sometimes decadal or even for centuries. The historical maps have an important role in further analysis and guidance of suitable implementation of NBS evaluation, perhaps more so in distinguishing former landscape functions than the exact spatial location of former measures.

A major source of uncertainty is known for the descriptions of both historic weather and historic land use and hydromorphology. The differences between 1900–1910 (resolution 1:20,000) and 1955–1965 (resolution 1:10,000) compared to the current landscape description are influenced by the lower resolution of historical maps and the possible omission of hydromorphological details, as the maps were created for different purposes (**Paper I**; Lindelöf, 2021). The difficulty to reconstruct historical hydrological features in landscapes has previously been explained by low spatial resolution of maps and to low frequency of updates compared to actual anthropogenic landscape alterations (e.g. MacVean et al., 2018). For example, in the Tidan catchment, the map used for 1900-1910, had a 54% higher wetland area than 2010-2020 while the length of the stream network and meandering increased (Lindelöf., 2021) as well as the number of lakes/ponds (+ 25%) (Table 1 in **Paper II**). The historical hydrological function of wetlands is difficult to depict due to the limited information in available historical data. Ideally, complementary observations in stream flows or groundwater levels, would help understand the hydrological functions of past- and current wetlands (i.e. being discharge, recharge or disconnection to groundwater and/or surface waterbodies). Thus, the location of historical waterbodies, flow. Hence, any estimate of historic water balance or “natural/reference state” becomes approximate. This have implications for both for quantitative and qualitative water management and challenge the evaluation of catchment management goals to limited negative effect on flow dynamics and the surrounding ecosystems depending on reference period.

6.3 Agricultural catchments showed increasing soil moisture drought under increased emission scenarios with similar trends, despite varying latitude and longitude

Soil moisture in agricultural landscape water balances for food/biomass production is of ultimate importance for the Swedish agriculture, with more than 90 % rainfed production. To complement existing limited soil moisture quantifications shown in Section 3.6, **Paper III** explored the current and future sensitivity of topsoil and subsoil water content, to investigate risks of early onset drought for seedlings during early root development, under near past-and future climate change in four agriculturally dominated catchments. The results showed a significant decreasing trend in soil moisture in the subsoil during the cropping season for the three catchments (Loftaån-Gamlebyån, Tidan (from June onwards) and Saxån-Braån (scattered week during the mid-cropping season, main reduction in Agust-September). On the contrary the results indicated of increased drying in the subsoil for the southern Saxån-Braån. Yet mainly significant with increased warming. The catchments located in the western part of Sweden showed significant early onset drying in May, while the trend is weaker and non-significant in July-August to increase again in September. In conclusion, all the catchments water balances indicated drier conditions during the cropping season, yet with growing severeness for especially Loftaån-Gamlebyån, Tidan and Saxån-Braån over time in future 2024-2060, compared to the reference period 1991-2023.

The results concerning soil moisture from four agricultural catchments in southern Sweden area were comparable to other studies, but emphasise and elevate the issue of drier conditions during the crop season while indicating a clearer pattern. This study added improved knowledge of scale (week) rather than longer (month- or year) as well as increased exploration of the full rootzone than just topsoil effects, which is the general layer available through e.g. satellite data or reanalysis products.

A study by Teutschbein et al., (2024) on historic soil moisture, indicated a trend of drying for 1961-2020 in the top 7 cm, using ERA-5 Land reanalysis data, a modelled dataset. Grusson et al. (2021), used a model approach based on the so called FAO-56 method in Allen et al. (1998), for 1989–2018 and 2021–2050 and concluded an effect of reduced soil moisture, but primarily for spring and early summer conditions, in 4 small agricultural catchments in southern Sweden . The work in **Paper III** contributed with an additional perspective on soil moisture trends using a model explicitly developed to include soil-water-crop interactions at the catchment scale and updated statistics for climate change using the latest CMIP6-climate statistics (Masson-Delmotte et al., 2023, Box SPM.1). **Paper III** furthermore estimated the difference in absolute threshold values with negative implications for crop production (Section 5.2.3).

The results presented here showed a reduction in actual evapotranspiration for all four catchments over time, starting from the middle to end of the cropping season, with the longest period of significant reduction occurring in Enköpingsån-Örsundaån, and the shortest in Saxån-Braån. This is contradictory to what has been shown in other studies. That is, the actual evapotranspiration is expected to increase, even in cases where soil moisture have shown a decrease or no change (e.g. Grusson et al. 2021b). The primary climatic drivers of evapotranspiration are temperature (which in Sweden has increased by 1.9℃ between 1861-1890 and 1991-2020 (Schimanke et al., 2022)), solar radiation (with potential change in incoming radiation from changed cloud cover and aerosols (e.g. Durand et al,. 2021; Myhre, et al., 2013)), wind speed (potentially decrease over Scandinavia, e.g. Jung & Schindler, 2019, CMIP5; Martinez & Iglesias, 2024, CMIP6), and humidity (where relative humidity has shown to remain overall stationary over time, i.e. enabling potential higher absolute humidity (Douville et al., 2022)). Hence, while the temperature increase drives an increase in ET_a, the full effect on climate change on *ET*a is dependent on increase or decrease in the other variables. In addition, Swedish crop production is overall energy limited[9]. This can potentially explain the increased response amongst vegetation to climate input since the mid-20th century, especially coupled to the observed precipitation increase nationally (Section 3.6.1). Indeed, energy limitation (ET_p per P) in Scandinavia seem to slightly increase or remain stagnant with climate change, while increasing in the evaporative index (ET_a divided by P) (Jaramillo et al., 2022). However, with decreasing, or stagnant soil moisture trends (section 3.6.5, **Paper III**), ET_a should theoretically be directed towards reduced volumes due to increased water limited conditions (e.g. section 3.1). The reduction or stagnation in soil moisture levels, despite increased precipitation, has been discussed as a result of soil moisture depletion by the increased ET_a and by shifting pathway of flows from infiltration into the soil, to higher runoff to streamflow (e.g. Destouni and Verrot, 2014; Grusson et al., 2021). However, with the same trends, the soil moisture reduction should eventually lead to decreased evapotranspiration rates.

6.4 Impact by climate change and anthropogenic interventions on the water balance in agricultural landscapes

The observed historic and estimated future effects on the water balance presented above (Section 3.6, **Paper II** and **III**) justify a need for increased possibilities for various irrigation strategies, which have been proposed by others, e.g., Grusson et al., 2021. Stream flow drought (defined as below the 20th percentile of streamflow) (Teutschbein et al., 2022) has been shown to increase both for south of Sweden, thus calling for improvement of water storage facilities during summer to facilitate irrigation requirements, where

[9] Incoming solar radiation is the limiting factor for crop growth and development rather than water availability.

the distance to available waterbodies have been concluded to be far for many farmers (Hoffmann et al. 2023).

There seems to be a divide between autumn and winter with increased streamflow. This thesis has mainly focused on the cropping season April to September. However, historically, soil moisture, streams and groundwater has been recharged during winters. Hence, the need for exploring the reverse pattern of waterlogging during autumn and winter is emphasised, which is expected to negatively impact winter-sown crops and soil operations due to reduced trafficability.

The studies presented in this thesis (**II** and **III**) did not explore and quantify the potential of individual measures for improving water retention and the synergetic effects of retention structures at the catchment level. To explore the effect of nature-based solutions on the water balance would be the next step in elaborating on the research presented in this thesis, with emphasis on exploring catchment characteristics leading to similar responses to specified types of measures and the location of implementation in the catchments.

6.5 Suggestion of improvements to study design.

Hydrological modelling is a compromise between using the best available in-data, research purpose, available processing power and project time. A simplified description of indata characteristics and processes should be done with expert knowledge of the effects of what is scaled away depending on the study purpose and study area. This also includes the decision of the model, where choosing a simpler model might be better if data is known to be missing (Sidle 2021). In **Paper II** and **III**, SWAT+ was selected as a process-based model due to its ability to model crop-water-soil dynamics; its dynamic data description concerning spatial objects; its well-tested ability to model different catchment conditions globally; and having high flexibility in included model variables compared to other hydrological models (e.g. Keller et al., 2023). The main challenge arising using the model in **Paper II** and **III** was that SWAT+ was relatively unresponsive in streamflow and evapotranspiration during calibration, even with large variations in calibration settings. Hence, the representability of peak flow and low flows was not entirely satisfactory, which has also been a challenge stated by e.g. Zhang et al. (2014), Farkas et al. (2016) and Piniewski et al. (2017). This was mainly attributed to snowmelt and allocation during the winter months in **Paper III** and generic under- and overestimating in **Paper II**. The calibration could have been further developed and possibly improved by using automatic calibration to explore a wider range of parameter combinations, as snow parameter has previously shown to successfully been modelled with SWAT (e.g. Grusson et al., 2015).

While one hydrological model was used for the work in this thesis, it is recognized that a multi-model approach can aid in removing uncertainty from the model results by reducing structural uncertainty (Horton et al. 2022). Furthermore, while the models in **Paper II** and **III** were set up with HRUs as land-description, a gridded model could aid in locating spatial effects of especially NBS and engineered structures, which would be important during potential future work building on **Paper III** to evaluate mitigation and adaptation efforts towards extreme weather.

Concerning the choice of climate model in **Paper III,** while the study setup emphasised on effects to soil moisture and evapotranspiration under future climate, the representation of the generated future climate series can be further developed. The choice of using a semi-parametric weather generator instead of downscaled series from climate models was motivated by the possibility to use the statistics from the latest climate predictions in CMIP6. These predictions have shown increased summer temperature and narrower precipitation space than CMIP5 (e.g. Kornhuber et al., 2023). In addition, available downscaled climate models (CMIP5) has been shown to overestimate precipitation events and underestimate drought compared to observed data (Grusson and Barron, 2022). Still, the generated precipitation in **Paper III** showed a reduction in variability and magnitude of precipitation events compared to the reference period (Figure 14). This is a challenge, as without sufficient representation of expected extreme precipitation outcomes, planning for extreme precipitation scenarios and consequently impact on other variables in the water balance will be impeded.

Models have extreme potential in scenario analysis, process data and explore effects of both natural and anthropogenically created systems. However, observed data is required to relate models to a realistic state. Representation of landscape spatial- and temporal data is increasing globally, especially by remote sensing (RS) products such as satellite data and the spatial- and temporal resolution is increasing. The potential of increased amount of indata such as RS-products have become more commonly used both as indata and for validation purposes to improves the potential use of physically based models. This was for example done in **Paper II** and **III** by using satellite derived values of ET_a. The validation of RS products and direct indata for hydrological models is however still challenged by reduced number of sampling sites, non-open source observed data. Hence, while remote sensing is evolving to larger coverage and resolution, a common ground and sampling for ground truth data is still required in order to capture the scale dynamic required, as well as having representative calibration data for models and verification of remote sensing products. This was also observed in Malmquist and Barron (2022), showing that modelled data for selected streams disagreed with observed streamflow data (Figure 17).

Naturally, improved data, spatial and temporal, enables exploration of more detailed processes and landscape dynamics. Better data further enable

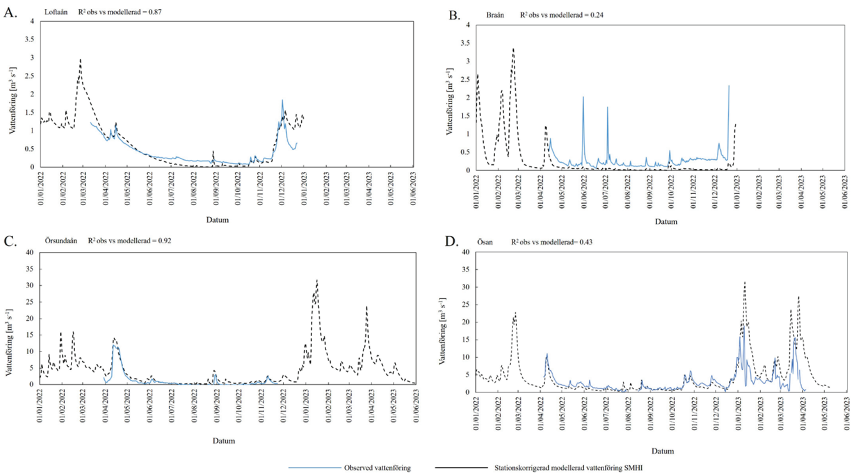


Figure 17. Observed (blue) discharge versus modelled (dotted) discharge from SMHI Hype model from the rivers Tidan, Loftaån, Braån and Örsundaån located within the four catchments and used for calibration in **Paper III**. From Malmquist and Barron (2022).

improved representation of heterogeneity at larger scale. It has been suggested that data sampled more frequently than daily, can show meaningful hydrological responses, especially in relation to extreme weather events where response time can be short (Hannaford et al. 2024). In addition, certain data, e.g. soil moisture, is difficult to cover over larger spatial areas for good spatiotemporal resolution of sample data. Yet, it is an important parameter for further evaluation of local agricultural water management and precision agriculture. To verify the accuracy of the modelled results, it opens for additional in-situ measurements also to parameters that require more elaborate measurement methods as well as exploring the full range of large available data sets provided from remote sensing.

7. Conclusion and future perspectives

- Landscape hydrologic functions modified by agricultural water management have the potential to be spatially and temporally further developed to improve the description of the catchment water balance in Sweden.
    - This thesis presented methodologies to derive three datasets with improved spatial representation of I) water holding capacity and saturated hydraulic conductivity, II) combined national stream network data adapted for agricultural land, and III) subsurface drainage.
    - By combining available national datasets through these methods, the spatial characteristics of water-holding capacity and saturated hydraulic conductivity; the length of flow pathways increased, and flow pathways intersecting with agricultural fields were better presented. Lastly, this thesis presented, which is to my knowledge, the first digital field map over spatial coverage of subsurface drainage in Sweden, with potential for further use in risk analysis and hydrological modelling.
- Comparing the effects of the historical and current extent of wetlands and stream networks did not show a significant change in water allocation in the mesoscale Tidan agricultural catchment. Yet, the low resolution of the historical maps challenges the possibility of converting the extent of waterbodies and streams and, therefore, fully depicting the historical hydrological landscape for use in restoration efforts and model studies.
- Soil moisture in agricultural soils is expected to decrease during the cropping season, with a more significant drying response in the subsoil than the topsoil. Data presented in this thesis showed that soil moisture will likely reduce over the entire season for southern catchments, with an initial reduction in the topsoil. This is an earlier onset compared to previous reported soil moisture reductions, increasing the potential risk and challenges for rainfed crop system.

- The results presented in this thesis emphasise the importance of expanding the presented work to additional agriculturally dominated catchments with a suggested Before-After-Control-Impact approach of extreme weather and effects of nature based and engineered solutions, structural as labour-based management

To extend the findings of this work, the following studies are recommended:

- The results and discussion in this thesis showed potential for better description of some key hydrological parameters to improve further our description of Swedish agricultural landscapes and water balance. There is a need to maintain existing monitoring stations and to extend the spatial and temporal resolution of especially soil physical data, and increase carefully considered sampling sites of stream flow and soil moisture. There is potential to improve the temporal scale to also capture climate extreme short term response, and especially for validation of both models and satellite data.

- The results and the reviewed literature presented in this thesis give a catchment scale overview of historical and future expected changes of increased evapotranspiration and drier soil moisture in southern Sweden, were the major cropping area is. The uncertainty in climate models and their representation of extreme weather and catchment properties, which largely govern the effects of implementation measures, a coordinated effort is suggested with focus on:
    - water availability to support a common framework and execution of evaluating risk areas
    - quantifying increased irrigation and drainage requirements on a local catchment level for increased water availability when needed. This type of analysis would benefit from inclusion of threshold of biodiversity and financial implications.

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Popular science summary

Water is essential for plants. It transport nutrients, enable biochemical reactions, fuels photosynthesis, act as cell support and in transpiration, occurring as a by-product of carbon dioxide uptake. Hence, crop production is susceptible to disruptions in water supply during the growth period. Rainfed production depends on adequate precipitation and the soil's ability to retain moisture, while irrigated crops receive water from external sources. Hence in either way, crop production is vulnerable to weather changes. At the same time, crops are susceptible to too much water by their roots, causing oxygen deprivation and reduced cell respiration. Additionally, temperature affects water requirements by increasing transpiration and internal metabolical and biochemical processes.

Humans have for centuries changed the landscape to improve the infiltrating capacity of soils and deviate water by changing the pathways of streams, constructing new or alternate pathways for water through ditches , and speeding up the drainage of the soils and wetlands (by open- and subsurface ditches) to improve soil water conditions and access land for crop production. In addition, damming of streams is a common measure for accessing water for irrigation. Hence affecting the natural state of the region. These landscape changes, together with altered land use, have impacted the water balance, simply described by the balance of the volume of incoming water equals outgoing water through evapotranspiration, runoff and stored water in the soil locally and on larger, i.e. catchment, basin scale, as water is not stationary. A catchment is a spatial area determined by topographical borders from which water flows into a stream or waterbody.

Water availability from precipitation and stored surface and groundwater is being challenged by climate change. Already occurring and future projections of climate change indicate increased temperatures, and changed volume and frequency of precipitation and longer periods of continuous warm temperatures. This challenges crop production by increasing the risk of both too little and too much water from precipitation and increasing water demand by increased temperatures. These risks call for adaptions and mitigation measures in arable landscapes to maintain soil infiltration and retention capacity. Withholding water in the landscape for diversion at sound pace and volume to be able to supply a sufficient amount of water for crop production under changed weather patterns. While still account for which margins there are to divert water without too much disturbance for other water users than agriculture. Up to present, mainly streamflow and evapotranspiration have been explored for changes due to land use and climate change. Hence, the aim of this thesis was to explore how the water balance in agricultural landscapes can be affected by climate change and human interventions.

In **Paper I**, this work began by improving how soil properties related to water infiltration were mapped, along with distinguishing natural streams from manmade ditches (both open and underground). The results showed that how soil texture is classified has a big impact on how infiltration and water storage are represented. Combining different datasets also revealed that the total length of streams and ditches was much greater than previously shown. Additionally, a new map was created to better represent underground drainage systems. To model the water balance, a hydrological model (Soil and Water Assessment Tool, SWAT+) was used in four catchments. These catchments, mainly agricultural to varying degrees, were located in southern Sweden (Götaland and Svealand) and chosen to represent different temperature and precipitation patterns in the country.

In **Paper II**, historical and current climates are compared. The respective historical water balance is then modeled one-at-a-time using different weather data and the varying degree of human alteration/presence of wetlands, streams, and open and subsurface ditches under current land use and climate, respectively. Modeling the water balance in the Tidan catchment for different levels of manmade water infrastructure changes in both historical and present-day landscapes challenges previous studies, which suggested that land use change had a greater impact on evapotranspiration than changes in weather (Section 3.6). While the effect was not significant, a reduction in wetland area appears to have decreased the landscape's ability to retain water, leading to an increase in streamflow volume.

In **Paper III**, SWAT+ was used to model the effect of future climate (2024-2060), namely temperature and precipitation changes, on soil moisture content and evapotranspiration. The modelling for historical water balance was done on one catchment, while the future scenarios were modelled for four catchments. Exploring the effects of future climate scenarios showed an increased drying trend with reduced soil moisture and increased evapotranspiration over time for three out of four catchments.

In conclusion, this thesis highlights a shift from human-driven landscape changes to climate as the dominant force affecting the water balance. It also reveals changes in how water is distributed between streamflow and evapotranspiration. However, accurately representing historical water bodies, streams, and water balance remains challenging due to variations in data resolution across time and space. While there is potential to use historical structures and stream delineation as a guide for the development of catchment storage and infiltration capacity of water. Soil moisture seems to experience increased drying with future climate change. However, there are ambiguous responses to soil moisture on the catchment scale of increased drying or stagnant over time. Hence, soil moisture needs further exploration of its response to climate impact.

Populärvetenskaplig sammanfattning

Vatten är nödvändigt för växters överlevnad och produktion. Vatten transporterar näring, möjliggör biokemiska reaktioner, ger energi till fotosyntesen, agerar som fysiskt upprätthållande stöd i celler samt är en viktig biprodukt vid växtens koldioxidupptag. I och med detta är växter väldigt mottagliga för störningar i vattentillgången under växtsäsongen. Regnförsörjd växtproduktion är beroende av tillräckligt regnfall samt jordens förmåga att binda fukten. Bevattnade växter å andra sidan erhåller vatten från externa källor, även om även det vattnet initialt är beroende av nederbördsmängd. Därmed är växtproduktion inom båda produktionsformerna känsliga för väderförändringar. Samtidigt är växter även känsliga för för mycket vatten i rotzonen då det orsakar syrebrist och minskad cellandning. Därtill påverkar temperatur växternas vattenbehov genom att öka transpiration och öka interna metaboliska och biokemiska processer.

Människor har i århundraden förändrat landskap för att förbättra markens infiltrationsförmåga och avleda vatten genom att ändra dess flödesvägar. Antingen genom nykonstruerade vattendrag eller genom avledning till alternativa flödesvägar för vatten genom diken. Dessa åtgärder har påskyndade dräneringen av jordar och våtmarker (genom öppna diken och dränering under mark) för att förbättra markvattenförhållandena och få tillgång till bördig mark för grödproduktion. Därtill har uppdämning av vattendrag varit en vanlig åtgärd för att komma åt vatten för bland annat bevattning. Därmed påverkar det naturliga uppströms och nedströms flödet i regionen. Dessa landskapsförändringar, tillsammans med förändrad markanvändning, har påverkat vattenbalansen. Vattenbalansen är balansen mellan inkommande vatten (nederbörd) och utgående vatten genom evapotranspration, avrinning och lagrat markvatten lokalt och på större, nivå d.v.s. avrinningsområdet. Ett avrinningsområde är ett rumsligt område som bestäms av topografiska gränser från vilka vatten rinner ut i en vattenförekomst.

Klimatförändringarna utmanar vattentillgången från nederbörd och lagrat yt- och grundvatten. Förekommande och framtida prognoser av klimatförändringar indikerar ökade temperaturer samt ändrad volym och frekvens av nederbörd och längre perioder med kontinuerliga varma temperaturer. Detta utmanar växtodlingen genom att öka risken för både för lite och för mycket vatten från nederbörd och ökar vattenbehovet genom ökade temperaturer. Dessa risker kräver anpassningar i åkerlandskap för att upprätthålla markinfiltration och retentionskapacitet samt för att kunna avleda vatten i landskapet i tillräcklig takt och volym för att samtidigt ha tillgång till tillräcklig mängd vatten för växtodling under torrare väderförhållanden. Samtidigt behövs en redogörelse för vilka marginaler det finns för att avleda vatten utan alltför stora störningar för andra vattenanvändare utöver jordbruket.

Fram till idag har främst vattenflöde och evapotranspiration undersökts som variabler för förändringar i vattenbalansen på grund av markanvändning och klimatförändringar. Därför var syftet med denna avhandling att utforska hur vattenbalansen i jordbrukslandskap kan påverkas av klimatförändringar och antropogena åtgärder.

I **Paper I** förbättrades en metod till hur markegenskaper relaterade till vatteninfiltration kartlades, tillsammans med att särskilja naturliga vattendrag från konstgjorda diken (både öppna och underjordiska). Resultaten visade att hur marktextur klassificeras har stor inverkan på hur infiltration och vattenlagring representeras. Kombinationen av olika datauppsättningar visade också att den totala längden av naturliga vattendrag och diken var mycket längre än i tidigare dataset. Dessutom skapades en ny karta för att bättre representera underjordiska dräneringssystem.

För att modellera vattenbalansen användes en hydrologisk modell (Soil and Water Assessment Tool, SWAT+) i fyra avrinningsområden. Dessa avrinningsområden var dominerade av jordbruk som markanvändning till varierande grad och var belägna i södra Sverige (Götaland och Svealand) och utvalda för att representera olika temperatur- och nederbördsmönster i landet.

I **Paper II** jämfördes historiskt och nuvarande klimat. Respektive historisk vattenbalans modellerades en i taget med historisk väderdata, varierande grad av mänsklig förändring/närvaro av våtmarker, naturliga vattendrag och öppna diken och täckdiken under aktuell markanvändning respektive klimat. Att modellera vattenbalansen i Tidans avrinningsområde för olika nivåer av vatteninfrastrukturförändringar i både historiska och nuvarande landskap utmanar tidigare studier, som tydde på att förändringar i markanvändningen hade större inverkan på evapotranspiration än förändringar i väderleken (avsnitt 3.6). Även om effekten inte var signifikant, tycks en minskning av våtmarksarealen ha minskat landskapets förmåga att hålla kvar vatten, vilket lett till en ökning av strömningsvolymen.

I **Paper III** användes SWAT+ för att modellera effekten av framtida klimat (2024-2060), nämligen effekten av temperatur- och nederbördsförändringar, på markens fukthalt och evapotranspiration. Modelleringen för historisk vattenbalans gjordes på ett avrinningsområde, medan framtidsscenarierna modellerades för fyra avrinningsområden. Att utforska effekterna av framtida klimatscenarier visade en ökad uttorkningstrend med minskad markfukt och ökad evapotranspiration över tid för tre av fyra avrinningsområden.

Sammanfattningsvis belyser denna avhandling en förändring från antropogent drivna landskapsförändringar till klimatet som den dominerande kraften som påverkar vattenbalansen. Arbetet i avhandlingen visar också förändringar i hur vatten fördelas mellan vattenföring och evapotranspiration. Att representera historiska vattenförekomster och vattenbalans är fortfarande utmanande på grund av variationer i dataupplösning över tid och rum. Även om det finns potential att använda historiska strukturer och utbredning av vattendrag som vägledning för utveckling av lagringskapacitet och infiltrationskapacitet i avrinningsområden. Markfuktigheten visar på ökad uttorkning med framtida klimatförändringar. Det finns dock tvetydiga svar på markfuktighet på avrinningsområdesnivå, med ökad torkning eller stagnerande variation över tid. Därför behöver påverkan på markfuktighet av klimatförändringar ytterligare kartläggning.

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With appreciation,
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Appendix

Table A 1. Structural interventions with direct or indirect effects on water retention in the catchments Enköpingsån-Örsundaån, Gamlebyån-Loftaån, Tidan and Sazån-Braån. Data is compiled from the national database Water Information Sweden (VISS) (Swedish County Administrative Boards, 2024), Geodatakatalogen (Swedish County Administrative Boards, 2024), personal communication with Västerviks kommun, (2023) and agricultural block data (Swedish Board of Agriculture, 2023).

	Catchment	**Enköpingsån-Örsundaån**	**Loftaån-Gamlebyån**	**Tidan**	**Saxån-Braån**
Best management practices for water retention	**Sub-category**				
Dams (no.])		19	5	8	7
Constructed wetlands (no.])		21	13		36
	Dry dams	8			5
	Wet dams	3			11
Underground macadam storage (no.])		1			
Adapted filter strips		7.7 ha			
Filter strips adjacent to waterbodies		424.3 ha	15.6 ha	52.6 ha	15.7 ha
Restoration of hydromorphology (no.])	Enabling up- and downstream of fish	1			6
Ditches (no.])	Swale				1
	Grassed waterways				2
	Macadam ditch				1
	Two stage ditch		2		1

Table A 2. Management practices with direct or indirect effects on water retention in the catchments Enköpingsån-Örsundaån, Gamlebyån-Loftaån, Tidan and Sazån-Braån. Data is compiled from the national database Water Information Sweden (VISS) (Swedish County Administrative Boards, 2024), Geodatakatalogen (Swedish County Administrative Boards, 2024), personal communication with Västerviks kommun, (2023) and agricultural block data (Swedish Board of Agriculture, 2023).+

Catchment **Best management practices for water retention**	**Enköpingsån-Örsundaån**	**Loftaån-Gamlebyån**	**Tidan**	**Saxån-Braån**
Structure liming	0 %	4.0 % (490 ha)	0	1.8 % (614 ha)
Catch crops with autumn tillage	0.003 % (7 ha)	1.4 % (175 ha)	6.6 % (4566 ha)	3.3 % (1096 ha)
Spring tillage	4.1 % (1309 ha)	1.2 % (148 ha)	3.2 % (2208 ha)	1.1 % (351 ha)
Applied permission for water outtake		1 %		
Tile drainage area per county	43 %	27 %	64 %	51 %

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Improving spatial resolution in soil and drainage data to combine natural and anthropogenic water functions at catchment scale in agricultural landscapes

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ABSTRACT

Discrepancies in time-space representation of indata and calibration/validation data obstructs analysis of hydrological processes thatlink natural and anthropogenic water infrastructure in catchments and landscapes. To improve indata for hydrological- and modelling of the soil-plant-atmosphere-continuum, this paper presents a high-resolution dataset of hydrological functions in the agricultural landscape of Tidan, Sw Sweden. We firstly address spatial representation of soil physical parameters, describing soil water flows and storage. Secondly, we derive tile drainage datasets from historical maps. Lastly, we explore delineation and spatial location of streams, ditches and waterbodies to improve description of water connectivity. The new soil datasets with top- and subsoil descriptions varied in depicting the sensitivity of saturated hydraulic conductivity and water holding capacity. The most representative soil map showed moderate (34%) - to very rapid (21%) saturated hydraulic conductivity, water holding capacity below 40 mm 10 cm^{-1} (94%) and a dry bulk density ranging between 1.2 and 1.8 g cm^{-3} (71%). The digitalization of drained fields suggests that 69% of the arable fields are under tile drainage, dominated by sandy loam, loam and clay loam. The combined stream network resulted in 5350 km of streams and ditches, + 14% km and + 129%, respectively, compared to available best resolution datasets. Landscape surface water storage increased with a small addition (+ 6439 m^3 storage potential) compared to previously available datasets. The improved descriptors of natural and anthropogenic flow and storage can potentially serve to improve water quantity and quality modelling under current and future climate- and hydrological changes.

1. Introduction

Balancing simplicity and complexity in the time-space domain of hydrological modelling is a classical dilemma when dealing with the soil-plant-atmosphere continuum (SPAC) (e.g., Blöschl and Sivapalan, 1995; Blöschl et al., 2019). Data and tools continuously increase in detail in space –time dimensions, especially satellite data (e.g., Sergieieva, 2022), models (Fatichi et al., 2016; Sidle, 2021) and processing capacity (Horton et al., 2022). The availability (or unavailability) of indata might enable (or inhibit) the use of more detailed and complex models in physical and conceptual functions that describe landscape hydrology and linked parameters (Wilby, 2019).

Remote sensed (RS) products and data synthesised from artificial intelligence (AI) have proven particularly useful as input for SPAC- and hydrological models. RS-products are widely used within the scientific community as model indata (e.g., Xu et al., 2014; Thakur et al., 2017; Tan et al., 2021) and in calibration-validation processes (e.g., Zhang et al., 2021). Increased detail in data, knowledge of soil-physical relationships, and more sophisticated models with higher computational capacity have been suggested as reasons to advance the use of physically based- rather than empirical models (Jarvis et al., 2022). Yet, the accuracy of hydrological parameters vary due to spatial and temporal

Abbreviations: AI, Artificial Intelligence; CMD, Coup Model soil data; DI, National ditch-network: ditches (Lidberg et al., 2021); DSM, Digital Soil Map; FAO-map, Soil textural map based on FAO soil textural classification; KTD, Soil profiles for forest (Karltun, 1995); M1, Economic Map - Original; M2, Economic Map – With tile drainage; RS, Remote sensed products; SC, Soil classes 1:25 000 – 1:100 000 (Geological Survey of Sweden 2014); SLD, SLU Soil Database (Wesström & Joel 2012); SPAC, Soil-Plant-Atmosphere-Continuum; STR, National stream network: topographically derived streams (Ågren & Lidberg, 2020); SV-map, Soil textural map based on Swedish soil textural classification; SCI, Soil and Crop Inventory; NSI, National Soil Inventory.

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resolution (e.g., Chao et al., 2021). The accuracy can furthermore be affected by the algorithm used to derive parameters from raw satellite data (e.g., Senkondo et al., 2019; Chao et al., 2021). Additionally, a mismatch in the time-space resolution of indata and calibration-validation data have potential implications for misalignment between scales, misinterpretation of results, or possibly the inability to achieve study objectives (e.g., Baffaut et al., 2015). The resolution of information for SPAC- and hydrological models also affect parameter settings and process sensitivity (e.g., Abbaspour et al., 2018). In some cases effect on parameter setting by resolution is also catchment dependent (e.g., Veith et al., 2010; Guse et al., 2017).

Sweden is an example of good national collections of open access, high-resolution spatial data linked to landscape description, such as topography and soil textural composition, as well as climate on a temporal scale. Nevertheless, parameters that typically directly influence hydrological flows are lacking in spatio-temporal representation. For example, most soil profile information only includes texture and occasionally soil organic carbon (Raulund-Rasmussen and Callesen, 1999; Jansson and Karlberg, 2004; Paulsson et al., 2015; Geological Survey of Sweden, 2018; Swedish Land Survey, 2019; Swedish University of Agricultural Sciences, 2021a). Few samples exist on parameters as, infiltration capacity, saturated and unsaturated hydraulic conductivity, water holding capacity and bulk density. These are fundamental to understanding soil physical properties governing hydrological partitioning, flow rates and water storage in soils. In hydrological catchment studies from Swedish arable landscapes, soil parameters have often been generalized to so-called type soils, with soil physical properties derived as generic parameters or from pedotransfer functions (Salazar et al., 2010; Johnsson et al., 2019). In other cases, the origin and/or estimates of soil parameters have not been fully presented in publications (e.g., Andréasson et al., 2004; Teutschbein et al., 2011; Davies and Beven, 2015; Arheimer and Lindström, 2019). Some studies (e.g., Jansson and Andersson, 1988; Grusson et al., 2021) that present their soil data have used soil physical data either directly from the SLU soil database (Wesström and Joel, 2012) or from in-situ soil sampling (e.g., Motovilov et al., 1999; Engeland et al., 2001, 2005; Verrot and Destouni, 2015, Smith et al., 2019, see compilation of studies in Malmquist, 2021a). The lack of detail concerning soil physical properties in these studies is either due to model configuration, where defined soil physical parameters are not required, or to the fact that the level of detail seems insignificant for the purpose of the specific study.

Another data gap is the lack of accurate delineation of manmade and natural streams. Information on stream pathways is somewhat accessible but limited to local applicability. Streams and ditches visible above ground are available as high-resolution datasets. Both potential locations of natural streams (Ågren and Lidberg, 2020), and manmade ditches (Lidberg et al., 2021), identify a much denser stream from topographic maps and "natural" pathways for stream formation, AI and image recognition, than those depicted in previously available maps. However, these maps do not capture subsurface tile drains and subsurface connections (e.g., culverts), which are important flow pathways. Especially in agricultural and urban catchments. The best available large-scale data on tile drainage plans is a modified version of the cadastral map (sv. Ekonomiska kartan) produced from orthophotographs between years 1935–1978. Although the maps are available as scanned- and georectified, they are not readily available for use in GIS-software and do not show the true outline of tile drainage pipes. Rather they show fields with available tile drainage plans. Neither do they include recent landscape changes, such as merged fields and shifts in spatial range over time or more recent installations of tile drains and related plans.

Anthropogenic landscape changes to land use, hydromorphology, and water storage, - withdrawal and -recharge, show alteration to evapotranspiration, runoff and soil water storage, compared to unaffected landscapes. Nevertheless, the direction of change is governed by area-specific properties, both internationally and nationally (e.g., Malmquist, 2021a; Kåresdotter et al., 2022). Hydromorphological changes (manmadeor natural) also has the potential to delay or reinforce flow patterns and alter their characteristics from perennial streams to more resemble ephermal streams, with possible further implications for, e.g., flora and fauna along streams or in waterbodies (Datry et al., 2023). Thus, a mismatch in the available spatial representation of key hydrological features - especially in landscapes with complex interactions of anthropogenic and natural waterways and storage – obstructs a thorough exploration of especially subsurface processes in catchment modelling. This is an issue, as evidence of synergies between engineered- and nature-based solutions to sustain effects of climate change on hydrological pathways is lacking (Miralles-Wilhelm et al., 2023). Thus, this paper explores the availability of high-resolution spatial data for developing the descriptions of hydrological functions in agricultural landscapes. The paper seeks to answer: *Can high-resolution data improve knowledge on anthropogenic modified hydrological functions?*

We illustrate this with three examples of spatial data adaptation to fit a catchment-scale hydrological model (here Soil and Water Assessment Tool (Arnold et al., 1998) for a Swedish agricultural catchment, SW Sweden. Our case study firstly addresses how to link point-data of soil physical properties to spatially distributed information on soil texture, in order to improve the representation of hydrological functions of soil water storage and water flows such as infiltration. Secondly, we develop spatial data for soils and their functions for water flows and storage under different degrees of anthropogenic modifications. That is i.e., "natural", and highly modified (subsurface /tile) drained soils. Finally, the delineation of streams, ditches and water bodies and effects of spatial location are explored. We discuss the implications on landscape hydrological functions for hydrological modelling.

2. Material and methods

2.1. Description of study area

Tidan catchment (696 km^2) is located in Västra Götaland County, Sw Sweden (58.6 N, 14.0 E/58.2 N, 13.9 E) in the temperate-boreal climate zone (Köppen zone Dfb, i.e., cold climate without dry season but with warm summers (Peel et al., 2007)) and zone 407 and 418 EU pedoclimate zones (Jones et al., 2010)). The landscape is heterogenous consisting of 24% (169 km^2) agricultural land, 21% (147 km^2) forest and 4% (29 km^2) urban land (Malmquist, 2021b) (Fig. 1). Tidan catchment represents a typical Swedish arable landscape with modified hydrological features and substantial surface- and subsurface drainage occurring over more than 150 years (Lindelöf, 2021). The area has historically been subjected to recurrent flooding due to high precipitation around the catchment, mainly occurring along stream Tidan, adjacent to river Ösan (Holmbom and Söderström, 2012; Wessberg, 2019), Dry spells/droughts have historically been a less recurrent issue (Holmbom and Söderström, 2012; Wessberg, 2019).

2.2. Data sources

The three datasets were developed from spatial raster- and polygon data collected from open-access databases provided by the Swedish Land Survey (*Lantmäteriet*), Geological Survey of Sweden (SGU), Swedish Board of Agriculture (SJV), Swedish Water Authorities (*Vattenmyndigheterna*), County administrative board of Västra Götaland, and additional peer-reviewed publications. Quantified parameter values as point- and tabulated data sets for soil texture and soil physical parameters were accessed from the SLU soil database (agricultural soils) and CoupModel soil database (forest soils) while data from additional peer-reviewed publications were analysed and used to develop all three datasets (Table 1 and Table 2).

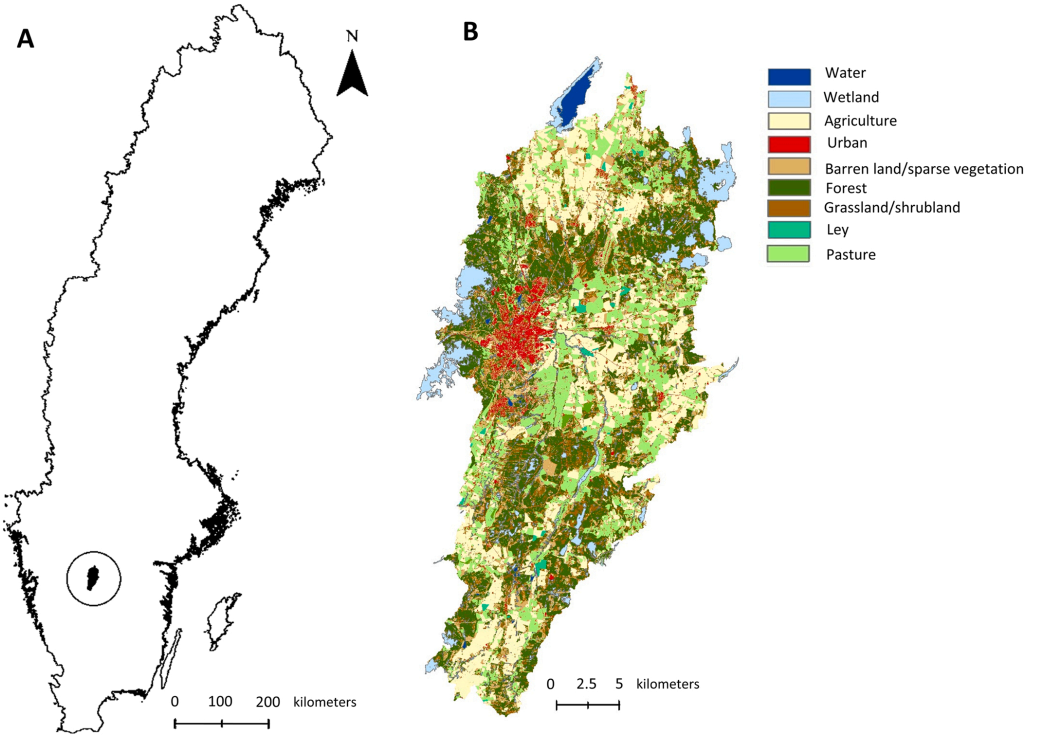

Fig. 1. Location of the study catchment, Tidan catchment (in the circle) (58.6 N, 14.0 E/58.2 N, 13.9 E) (A) and land use map of Tidan catchment for year 2020 with major land use classes (B).

2.3. Methodology

2.3.1. Linking soil physical properties of infiltration in soil profiles, water holding capacity, natural drainage and groundwater recharge to soil textural datasets

2.3.1.1. Arable soils. Soil profiles with information on soil physical properties (saturated hydraulic conductivity, soil organic carbon, dry bulk density and plant available water) from SLU's soil (Wesström and Joel, 2012) database (hereinafter *SLD*) were firstly classified to soil textural classes after the Swedish soil groups in the soil map *soil classes 1:25 000 – 1:100 000* (Geological Survey of Sweden, 2014) (hereinafter *SC*), as geological and agricultural soil particle classification systems use different grain size divisions (Supplemental material, Fig. S2). The soil profiles were additionally classified based on FAO textural classes to fit soil classification layers of topsoil from the digital soil map (Piikki and Söderström, 2019) (*DSM*). The soil physical profile point-data and soil textural layers from *DSM*, respectively, were associated with glacial/postglacial origin in *SC* and subdivided by their geological origin and soil textural class.

Two soil maps with soil physical properties were created. One was based on FAO-textural classification *(FAO-map)* by associating the soil profiles of unique geological- and textural classes from *SLD* to the closest individual soil pixel in *DSM* of same geological origin and FAO-textural class. The second map was based on Swedish soil classes (*SV-map*) and the nearest pixel from the subsoil layers of *SC*. Some soil classes in *SLD* at topsoil (0–10 cm) and subsoil (40–60 cm) were not available from all the various soil texture classes present in *DSM* and *SC* of Tidan catchment. To fill this gap in *SLD*, they were fitted to the closest soil class with the closest similar textural composition available in *DSM* and *SC*.

2.3.1.2. Organic soils. Physical parameters for organic soils are limited in the source material (Table 1). Thus, physical parameters were assigned based on their organic type (e.g., gyttja soil, bog peat or fen peat) and proximity to the study area based on soil profiles from Berglund et al. (1989) and Berglund (2011).

2.3.1.3. Forest soils. Soil texture for forest soils is available as spatially located polygons and point data while soil physical data are lacking (Department of Forest Resource Management and Department of Soil and Environment, 2022). For our dataset, we used a compilation of 24 forest soil profiles on glacial till (Karltun, 1995) (henceforth KTD) containing the bulk density and volume weight of particle size fractions for three east-to-west directed transects in southern, central and northern Sweden. For the new soil dataset, we combined soil profiles from forest land use from the Coup Model (Jansson and Karlberg, 2004) (henceforth CMD), with profiles from KTD, based on the closest value of soil carbon in topsoil (5–15 cm) and subsoil (40–60 cm). The matching profiles' saturated hydraulic conductivity was assigned based on topsoil organic carbon content. Bulk density values were then matched individually per each soil layer from the assigned profiles to achieve a realistic variation of saturated hydraulic conductivity with depth. Soil organic carbon has been shown to vary with topography and hydrologic class (e.g., Callesen et al., 2003; Olsson et al., 2009). Thus, the profiles

Table 1
Source data of soil physical parameters and spatial soil textural information used to construct an improved high-resolution soil physical properties map at catchment scale in Tidan catchment, SW Sweden. The original name of the datasets are presented in column "Map/indata".

Dataset	Year of production/ observation	Map/indata	Acronym	Resolution (period, time step, area)	Data type	Source
Soil textural and physical parameters	2016	Digital soil map: soil classes & texture	DSM	50 × 50 m, national coverage to Gävleborg county	Raster	Piikki and Söderström (2019)
	2014	Soil classes 1:25 000 – 1:100 000: classes based on Swedish soil classification	SC	National coverage. Layer JG2 – representing subsoil at approximately 50 cm	Polygon	Geological Survey of Sweden (2014)
	2018	Soil depth model 2020: gridded soil depth from point sources		10×10m	Polygon	Geological Survey of Sweden (2020)b
	2015	Sequence of soil layers: soil texture		National coverage	Point	Geological Survey of Sweden (2015)
	1952–1973**(a)**; 1956–2007**(b)**; 1982 – 1987**(c)**; 2002–2003**(d)**; 1988–1990**(e)**;1991**(f)**; *no date-generic* ***(g, h, l)****; no date – laboratory* ***(i,j,k)****; no date given – various samplers* ***(m)***	Soil profiles: texture; moist bulk density; dry bulk density; water holding capacity; impermeable soil layer; loss on ignition[a]	(a) SLD, (b) CMD (e) KTD	0–100 cm	Point	**(a)**Wesström and Joel (2012)[b] **(b)** Jansson and Karlberg (2004); **(c)** Berglund et al., (1989); **(d)** Berglund. (2011); **(e)** Karltun (ed) (1995); **(f)** Wikner et al. (1991); **(g)**Vägverket and Räddningsverket (1998); **(h)**Ferdos et al. (2015); **(i)**Mulqueen (2005), **(j)** Zhang et al. (2011); **(k)**Li et al. (2021), **(l)**Wallman et al. (2018) ; **(m)**Carlsson and Carlstedt (1977)
	1988–2017	Soil and crop inventory: soil texture		0–20 cm; 40–60 cm	Point	Swedish University of Agricultural Sciences. (2021a)
	2011–2012	National soil inventory: soil texture		0–20 cm	Point	Paulsson et al. (2015)
	2003–2012	Swedish National Forest Inventory: soil texture & soil organic carbon		0–20 cm; 40–60 cm	Point	Swedish University of Agricultural Sciences (2022a)

Note: (a) Not all parameters are present for all soil profiles
(b) Based on publications by Andersson and Wiklert (1977a, b,); Andersson et al. (1983a, b, c); Wiklert et al. (1983a, b, c, d)

Table 2
Sources and indata used for delineating tile drained fields from historical maps, adjust stream- and ditch network to a combined network of watercourses, and data to extract water bodies in Tidan catchment, SW Sweden.

Dataset	Year of production/ Observation	Map/indata	Acronym	Resolution (period, time step, area)	Data type	Source
Stream network	2021	National ditch-network: ditches	DI	National coverage	Raster	Lidberg et al. (2021)
	2020	National stream network: topographically derived streams	STR	National coverage	Raster	Ågren and Lidberg (2020)
	2020	Property map, stream layer		National coverage	Polyline	Swedish Land Survey. (2021)
	2021	Digitized streams, year 2018		Tidan catchment	Polyline	Lindelöf (2021)
	2014	Ditch network: ditches, pipes and embankments		Västra Götaland County	Polyline	County Administrative Board of Västra Götaland (2021)[a]
Water bodies	2021	Database of constructed wetlands		National coverage	Polygon	SMHI (2021)
	2020	Swedish Water Archive; waterbodies		National coverage	Polygon	SMHI (2020)
	1981–2005	National wetland inventory		Scale 1:250 000, wetlands > 20 ha, National coverage	Polygon	Swedish Environmental Protection Agency (2021)
	2021	Wetlands and immersed grass surfaces for water retention and –infiltration (sv. *torrdammar)*			Point	*VISS,* Vattenmyndigheterna, Länsstyrelserna, Havs- och Vattenmyndigheten
	2013	National dam database			Point	SMHI, dam and lake register (http://vattenwebb.smhi.se/svarwebb/)
	2002–2021	Meadow and Pasture Inventory (TUVA)			Polygon	Telenius and Nordberg (2021)
	2018	National Land Cover Database (NMD: open wetlands		National coverage	Raster	Swedish Environmental Protection Agency. (2020)
	2015–2020	Agricultural block database: wetlands		National coverage	Polygons + table	Swedish Board of Agriculture (2020)
Drainage	1935–1978	Economic map (year 1935–1978)	(M1 base map, M2 map depicting tile drainage)		Scanned paper maps	Swedish Land Survey. (n.d)
	2014	Soil drainage network: historical ditch systems from mid-19th century				County Administrative Board of Västra Götaland (2021)

Note: (a) also used to evaluate tile drainage system were associated to spatially distributed hydrological classes, stating three qualitative classes of presence/absence of moving soil water. The position was based on the slope position (Department of Forest Resource Management and Department of Soil and Environment, 2022) of spatially verified soil profiles from the Swedish National Forest Inventory (Swedish University of Agricultural Sciences, 2022a). The linked soil profiles were spatially joined to subsoil layers from *SC* for land not classified as arable land, based on soil texture class (40–50 cm) from KTD and the Swedish University of Agricultural Sciences (2022a) to determine the association with the geological formation and sorting of material, i.e., till or no-till.

2.3.1.4. Gravel, boulder ridges and bedrock. Soil physical parameters for profiles dominated by coarser particle size are scarce as most soil physical property analyses are done on (cylinder) cores with a finer soil particle fraction, i.e., particles < 2 mm (e.g., Stendahl et al., 2009). However, the density of minerals in the Swedish bedrock is relatively homogenous (e.g., Knutsson and Morfeldt, 1973; Carlsson and Carlstedt, 1977; Wikner et al., 1991; Vägverket and Räddningsverket, 1998; Larsson, 2008; Wallman et al., 2018). Hence, values on bulk density and saturated hydraulic conductivity for gravel and bedrock were estimated as median values from data by Carlsson and Carlstedt (1977); Wikner et al. (1991); Vägverket and Räddningsverket (1998); Mulqueen (2005); Zhang et al. (2011); Ferdos et al. (2015); Wallman et al. (2018) and Li et al. (2021). Values on plant available water in the root zone for gravel and boulder soils were based on generic profiles from *CMD* and compared with profiles of gravel and bedrock from the American soil database SSURGO ((Soil Survey Staff, 2021).

2.3.1.5. Soil depth. The two soil maps were merged with available soil depths from the Soil Depth Model 2020 (Geological Survey of Sweden, 2020). As a majority of the soil profiles in *KTD* and *SLD* were sampled to a depth of 1 m, the physical properties below 1 m are unknown. To join the soil depth map to the soil physical layers, the depths of the soil profile layer sampled at 0.9–0.1 m from *SLD* were adjusted to the depth from the Soil Depth Model 2020 (Geological Survey of Sweden, 2020) if > 1 m. In case of soil depths < 1 m, the respective soil layers below were erased from the final spatial dataset. The schematics of how we linked soil physical parameters to soil textural data is presented in Fig. 2.

2.3.2. Delineating tile drained field

A specific purpose of this study was to develop indata combining natural and manmade waterbodies at catchment scale. Approximately 64% (300087 ha) of agricultural land is tile drained in Västra Götaland region (SCB and Swedish Board of Agriculture, 2018), yet with a high likelihood of additional forested areas being drained. To develop a map of tile drainage in Tidan catchment, we used information on tile drained fields from the historic Swedish Economic Map for the years 1935–1978 (Swedish Land Survey). Copies of the Swedish Economic Map (years 1935–1978) include fields marked with available individual tile drainage plans, compared to the original economic map that only showed field borders. Henceforth the original map is stated as M1 and the map with marked tile drainage plans M2. The colour setting of land uses and objects in the maps enables the classification of borders between land-use classes and individual fields which further enables extraction of fields that are/have been under tile drainage.

The scanned tile drained fields in M2 were laid over and geo-rectified to M1. The two map versions were classified after colour settings by ISO

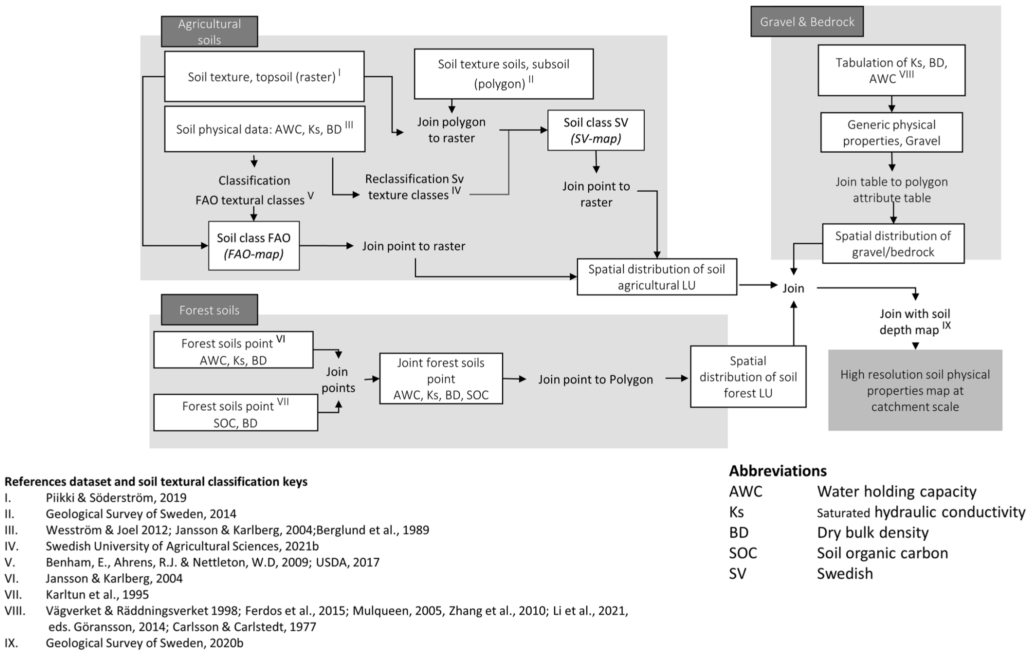

Fig. 2. Methodological approach as flowchart for the developing of a catchment scale high resolution soil physical properties map. The three light grey boxes show the separate processing of agricultural soils, forest soils and gravel and bedrock soils respectively. Other landuses than the just mentioned, were assigned soils from the agricultural soil dataset. Footnotes show the respective dataset that were used per processing step. White boxes indicate a new dataset, while free-standing texts indicate a processing step.

cluster unsupervised classification (ESRI, n.d.a). The number of classes were set to n = 10 (ESRI, n.d.b), and classes representing field boundaries and line-objects were extracted to separate layers, based on their land use class attribution from the unsupervised ISO classification. Thereafter they were transformed from raster to polyline files. The boundaries around agricultural fields from M1 were erased from M2. This resulted in maps with only diagonal lines representing fields with available tile drainage plans. Due to some misalignment during the rectification of the dataset, a buffer distance of 15 m from the border lines was included when erasing the borders. This to ensure that their full extent was erased.

2.3.3. Delineation and extent of stream- and ditch network

A comparison of the two recent datasets over stream networks (Ågren and Lidberg, 2020) (STR) and ditches (Lidberg et al., 2021) (DI) indicated misalignment for Tidan catchment. The topographic stream network particularly depicted water courses in arable land not present in orthopohotographs (Swedish Land Survey, 2018, resolution 0.25 m). Thus, the two datasets were processed to link and erase false streams for the best possible depiction of the catchment stream network. In addition, ditches from manually digitized maps depicting drainage ditches from the national county administrative boards verified from the mid-19th century were included (available at https://ext-geodatakatalog.lansstyrelsen.se/GeodataKatalogen). For Tidan catchment, the drainage network is dated from 1885 to 1971. Some of this dataset was not included in the more recent ditch network in *DI*.

The three datasets were combined to achieve a connected stream network consisting of both natural streams and man-made ditches. The streams in *STR* were overlaid and snapped to DI with a buffer distance of 30 m based on visual judgement. Stream network segments that shared a line with the ditch network were selected as true connectivity, and overlapping line segments of the topographic stream network were erased. The stream segments in *STR* overlapping agricultural fields were erased since natural streams are eliminated by the presence of sub- or surface drainage systems (Section 2.3.2). Lastly, the segmented topographic stream network and the ditch map were merged into a joint layer, depicting the final stream network.

Some of the main streams were not included in the above-detailed stream network maps. Hence, polylines for the main river in the catchment (*Ösan*) and streams delineated for the specific catchment by Lindelöf (2021) were snapped to the combined stream-ditch network (60 m buffer based on visual judgement, reduced by overlapping line segments, and merged to the detailed stream network dataset. The final layer was then manually adjusted by connecting line segments to gaps along river Ösan.

2.3.4. Water storage in natural and manmade lakes, reservoirs and wetlands

The locations of constructed wetlands are not always depicted correctly, or are fully missing within national databases (e.g., ter Borg and Barron, 2021). Thus, locations of constructed and natural wetlands within Tidan catchment were verified with Sentinel 2 images. Three maps with different colour band combinations were created to capture presence of waterbodies, i.e., the Modified Normalized Difference Water Index (Xu, 2006) with SWIR2 data, the Color Infrared Vegetation Map (band NIR, Red and Green) and Land/Water images (bands NIR, SWIR1 and Red). Moreover, the classified waterbodies were manually controlled and labelled as "true" or "false". Waterbodies classified as "true" were compared with national registers from the wetland database, constructed wetlands, wetland inventory and agricultural areas from the agricultural block database (Table 2). The classification of waterbodies are arbitrary as definitions for the three classes of waterbodies intersect (e.g., Langbein and Iseri, 1960; World Meteorological Organization, 2012; Tiner, 2017). However, the three classes here were limited by waterbodies classified as reservoirs if they intersected with the newly delineated stream network. Ponds were classified as open waterbodies if not intersecting with a stream network and wetlands if they contained visible vegetation.

2.3.5. Mathematical processing of datasets

The new soil texture maps (*SV-map* and *FAO-map*), the combined stream- and ditch network (DI) and delineated waterbodies were compared spatially with respective original datasets (Table 1, Table 2). All spatial analysis of data were done in ArcMap 10.8.1 (ESRI, n.d.c), while comparison of stretch-, areal- and volume between new- and original datasets were analysed in Excel2016 (© 2016 Microsoft Cooperation).

The fit of soil physical profiles to soil textural maps were compared with point textural data from Soil and Crop Inventory (*SCI*) (Swedish Land Survey, 2019; Swedish University of Agricultural Sciences, 2021a) and National Soil Inventory (*NSI*) (Paulsson et al., 2015) by fitting a simple linear regression between the datasets, with soil texture as single explaining variable (data not shown). Soil physical data (saturated hydraulic conductivity, water holding capacity and bulk density) were extracted per soil texture class, soil layer (top- or subsoil) and per undrained and drained areal respectively. Field area per class was calculated in the attribute table of the layer or respective soil physical property by *calculate geometry*. The absolute area was summarized per class and estimated as share (%) per soil texture- and drainage class (drained vs undrained fields) by dividing the share per soil texture class with total catchment area, The soil texture and soil physical properties per drainage class were divided per total area agricultural land.

The length of *DI* and *STR* and the new combined dataset was estimated by *calculating geometry* in the attribute tables. The variation in length between the datasets was calculated as the difference between the new dataset and DI respective STR.

The estimated area and volume of the waterbodies were summarized per class of waterbody (i.e. pond, reservoir or wetland). The area and volume of unique lakes not present in available datasets were extracted from the new combined datasets, and summarized separately.

3. Results

3.1. Assigning soil physical parameters for best fit to soil texture classes

The final soil dataset included n = 45 individual soil profiles in the *FAO-map* and n = 35 in the *SV-map*. This is somewhat counter-intuitive, as the Swedish soil classification system includes more soil texture classes than the FAO system (Table S1). As Swedish soil classes are lumped if classified by the FAO classification system, a higher number of soil profiles is assigned per FAO soil class compared to the Swedish system. Thus increasing the overall number fitted per soil pixel to the nearest fit. Hence, there is an increased number of final included profiles in the *FAO-map* (Fig. 3). The two datasets further differed in their lumping of the FAO soil classes, with a more diverse distribution of fine-medium particle classes for the map based on FAO-classes (Table 3).

The two soil datasets were further used to calculate the spatial distribution of saturated hydraulic conductivity (Table 4, Fig. 4a), water holding capacity (Table 4, Fig. 4b) and bulk density (Table 4). The spatial distribution of soil physical characteristics differs depending on the input soil texture data using Swedish or FAO texture classification. The soil physical datasets based on the *SV-map* have the largest area of moderately slow (44%) and very rapid (29%) saturated hydraulic conductivity, whereas the water holding capacity is mainly in the interval of 20–40 mm 10 cm^{-1} (82%). The bulk density is mainly in the interval of 1.2 – 1.4 g cm^{-3} (44%) and 1.6 – 1.8 g cm^{-3} (17%). In the subsoil, the saturated hydraulic conductivity is lower than in the topsoil, with the largest in the slow (17%) and moderate (48%) categories. The water holding capacity in the subsoil is distributed between 0 and 20 mm 10 cm^{-3} (44%) and 20–40 mm 10 cm^{-3} (41%), while the distribution of bulk density is mainly in the interval 1.2–1.8 g cm^{-3} (48% in the

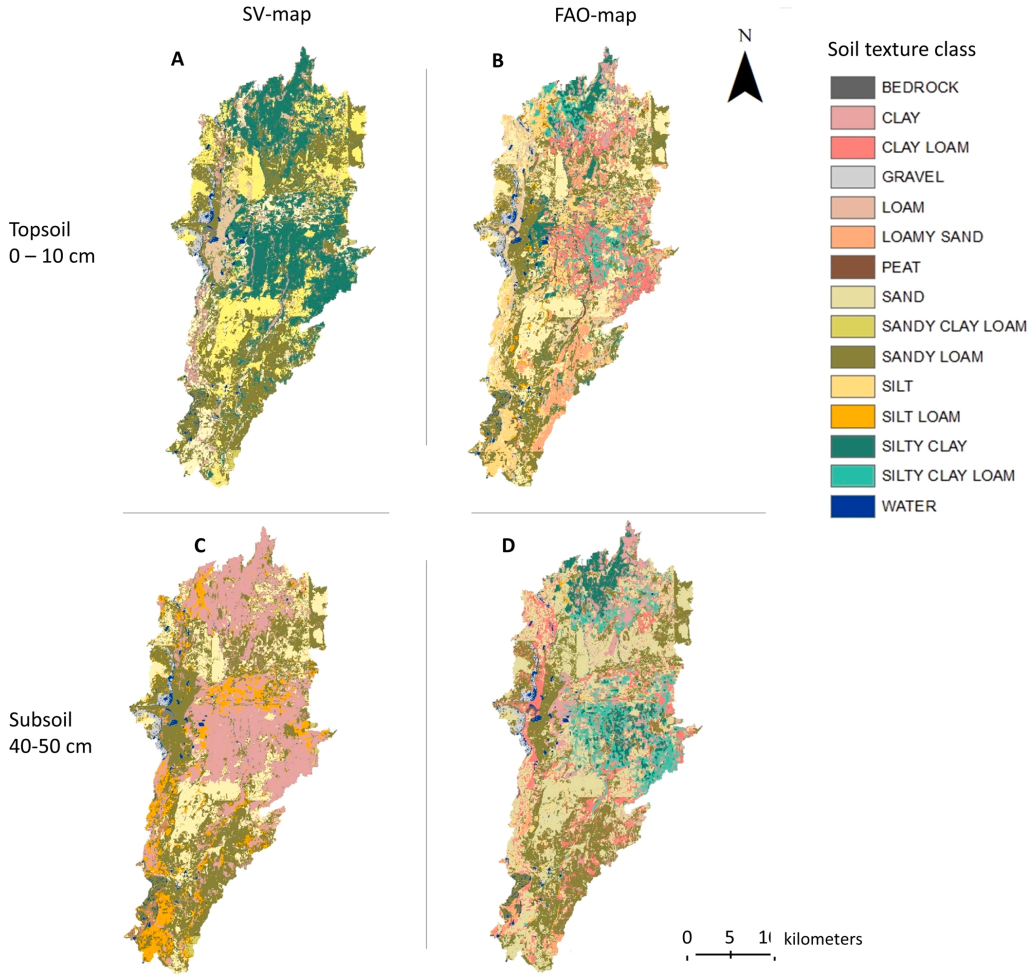

Fig. 3. New soil textural maps in Tidan catchment with fitted soil profiles based on Swedish soil classes (SV-map) (A & C) and FAO/USDA soil classes (FAO-map) (B & D). The right and left column show the SV-map and FAO-maps respectively, while upper two maps show topsoil (0–10 cm) and the lower to soil maps show subsoil layers (40–50 cm). The soil texture is based on soil profiles from the SLU soil database (Wesström and Joel, 2012) and fitted to soil map of Piikki and Söderström (2019).

interval of 1.4 – 1.6 g cm^{-3}). For the input from the *FAO-map*, the largest area in the catchment has a moderate (34%) - to very rapid (21%) saturated hydraulic conductivity, and the water holding capacity is below 40 mm 10 cm^{-1} soil (94%) in the topsoil. These values are reflected in the soil classes of sand, sandy loam, silt loam and loam, which constitute the larger areas in the catchment. Bulk density is between 0.8 and 1.6 g cm^{-3} in the topsoil and increases in the subsoil to the interval 1.4–1.8 g cm-3 (Table 4).

Comparing the two soil datasets, two things stand out. The FAO-map dataset results in larger area of rapidly saturated hydraulic conductivity, which might impact infiltration at precipitation events. However, the water holding capacity is lower over a larger area compared to the *SV-map*. This increase the risk of drought impact. The highest saturated hydraulic conductivity areas are distributed spatially in the centre of the catchment/along stream -and ditch network and water bodies to a greater extent than the Swedish derived data (Fig. 4a). Due to a lack of stand-alone datasets of soil texture and soil physical properties, the datasets have not been independently validated.

3.2. *Identification and delineation of tile drained fields on landscape scale*

The extraction of fields with tile drainage plans from the economic map (Swedish Land Survey, n.d.) in Tidan suggests that 69% (205 km^2) of the arable fields within Tidan catchment have tile drainage plans available. This is in line with the official statistics of drainage in Västra Götaland from 2016 where 64% of the agricultural land was under tile drainage (SCB and Swedish Board of Agriculture, 2018). Combining the delineated tile drainage field with the soil texture map classification

Table 3
Area of soil classes for Tidan catchment SW Sweden and the share of soil classes in fields with tile drainage plans extracted from the economic map (years 1935–1978) (Swedish Land Survey n.d).

Soil texture class	Area [km^2]				Soil texture area drained of total area [%] (Topsoil)[c]	
	SV[a]		FAO[b]		SV	FAO
	0–10 cm	40–50 cm	0–10 cm	40–50 cm		
Clay	23	232	10	58	1.0	1.1
Clay loam	0	0	47	84	0.0	5.7
Peat	1	1	5	1	0.0	0.0
Gravel	7	7	7	7	0.0	0.0
Loam	43	2	50	3	0.8	3.4
Loamy sand	2	6	75	8	0.1	0.3
Sand	117	126	140	235	0.2	1.1
Sandy clay loam	3	3	2	0	0.0	0.0
Sandy loam	216	240	173	168	5.1	4.8
Silt	0	0	0	9		
Silt loam	64	69	82	3	4.3	6.1
Silty clay	209	0	62	45	16.5	2.6
Silty clay loam	0	0	32	65	0.0	3.0
Water	9	9	9	9	0.0	0.0
Bedrock	2	2	2	2	0.0	0.0
SUM	**696**	**696**	**696**	**696**	**28**	**28**

Note: (a) Show area [km^2] per soil textural class for soil maps (topsoil and subsoil) derived based on Swedish soil classification system (SV-map).
(b) Show area [km^2] per soil textural class for soil maps (topsoil and subsoil) derived based on FAO/USDA soil classification system (FAO-map).
(c) Present the area per soil class [%] with available tile drainage plans based per soil textural map based on either Swedish classification system (SV) or FAO/USDA soil classification system (FAO)

(Section 2.3.1) shows that mainly sandy loam, loam and clay loam were drained (Table 4). The final map of fields with tile drainage plans showed higher clay content (median 17% ± 13 SD) compared to undrained fields (median 14% ± 10 SD) and lower sand- and silt content (Fig. 5).

3.3. Alignment of natural and manmade stream network

The combined stream and ditch network resulted in 5350 km of streams and ditches within Tidan catchment, showing a landscape of more water flow infrastructure than previously identified for the catchment. This is an increase of 649 km compared to *STR* and an increase of 2927 km compared to *DI* (Table 5). Of the topographic stream network, 2690 km lie on agriculturally managed fields, with 2470 km not intersecting with the ditch network. Thus, the topographic stream network identified on agricultural land was assumed to be falsely delineated, as field management, ditch networks and tile drainage systems that reallocated streams that would otherwise have occurred naturally due to topography. Approximately 269 km of the total length of the ditch network (774 km) from the County Administrative Board of Västra Götaland (2021) intersects with tile drained fields identified under Section 2.3.2, and these are not depicted in *DI*. A buffer of 5 m was used around the ditches from Lidberg et al. (2021) to extract non-intersecting ditches from the County Administrative Board of Västra Götaland (2021), thus some segments are missing in the total length estimate.

There is a difference, with a median of 35 m ± 0.72 m, between the AI delineated ditches and closest vertices of the topographically delineated stream network, despite using the same topographic maps as base maps. Ditches in topographic maps should be visible if the resolution with an average width in the ditch map is higher than 2 m ± 1.3 m (Lidberg et al., 2021). Thus, it can also be expected to initiate stream delineation from topographic maps at the same location as the ditches when using topographically governed stream delineation tools in GIS-software, where flow direction- and accumulation is identified by the lowest topographic cell neighbours (Schäuble et al., 2008; López-Vicente et al., 2014) (Fig. 6).

3.4. Land cover corrected for natural and constructed water storage

In total, n = 6 additional water bodies were identified from satellite images (Copernicus Sentinel Data, 2020a, b) and orthophotos (Swedish Land Survey, 2018), comprising a total surface area of 4.3 * 10^{-3} km^2 and an estimated volume of 6.4 * 10^3 m^3 (Table 6), compared to readily available databases (SMHI, 2020, 2021; SMHI, n.d; Swedish Board of Agriculture, 2020; Swedish Environmental Protection Agency, 2021; Vattenmyndigheterna, Länsstyrelserna, Havs- och Vattenmyndigheterna, n.d.). This is a small addition compared to the total area and volume of delineated water bodies from previously known datasets (surface area 1.82 km^2, volume 2.68 *10^{-3} km^3) combined (Table 6). Although the added area/volume the waterbodies is small, they can still possibly impact water balance if they are located in hydrologically important spaces.

4. Discussion

4.1. Opportunities and limitations in the three new datasets

The new datasets increased spatial resolution via a weighting approach for point to pixel derived from measured soil physical properties governing soil hydrological properties rather than pedotransfer functions, using point measured soil texture as input. The dataset also accounts for multiple soil layers not (fully) depicted in existing national datasets (see references Table 1), an issue also noted in commonly used global soil datasets (e.g., Batjes, 2009; IASA et al., 2012; Origiazzi et al., 2018). The resolution in the new soil dataset remained 50 × 50 m, after the base map (*DSM*) (Piikki and Söderström, 2019). This is, however, the best available resolution dataset for Sweden, compared to the map (*SC*) by the Geological Survey of Sweden (2014) and, e.g., European (Panagos, 2006; Kristeensen et al., 2019) or global datasets (IASA et al., 2012; Global Soil Data Task, 2014), which are based on interpolated values or derived from correlated parameters.

The increased number of soil profiles per soil textural group for the dataset based on FAO soil classification (*FAO-map*) compared to the Swedish classification *(SV-map)* expanded the spatial variation of soil physical properties within the catchment and their respective soil physical properties. The dataset based on FAO classification resulted in an addition of n = 35 (n = 25 with Swedish classification) soil profiles compared to, e.g., the set of generic soil profiles (n = 10) used in calculations of nutrient leakages and environmental impact from soils to waterbodies on both a multi-catchment and national scale (Johnsson et al., 2019). Thus, the method presented herein is one alternative for increasing the spatial representation of soil physical properties, not only in Tidan catchment, but also as extended to other catchments to enhance the representation of soil heterogeneity.

As no stand-alone dataset was available for the validation of either soil texture or soil physical properties, the new soil physical dataset should be used with caution. A common issue is the backtracking of Swedish spatial soil physical datasets to the sampling in Soil and Crop Inventory and National Soil Inventory (Paulsson et al., 2015; Swedish Land Survey, 2019; Swedish University of Agricultural Sciences, 2021b), resulting in the absence of independent datasets. To our knowledge, only three additional compiled datasets (Geological Survey of Sweden, 2018; Jansson and Karlberg, 2004; Raulund-Rasmussen and Callesen, 1999) of quantified soil texture composition for land uses other than agricultural ones are available for Swedish soils. Two of these datasets were used for the delineation of our new soil datasets. The dataset from Raulund-Rasmussen and Callesen (1999) was not accessible at the time of our

Table 4
Area distribution of saturated hydraulic conductivity, water holding capacity and dry bulk density of the intervals 20 mm 10 cm^{-1} and 0.2 g cm^{-1}, respectively in Tidan catchment, SW Sweden. The columns named "SV" represents values from soil physical maps originating from soil maps based on Swedish soil classification system (SV-map) and columns named "FAO" represent values from soil textural maps based on FAO/USDA soil classification system (FAO-map).

Saturated hydraulic conductivity[a] [mm h^{-1}]	Area [km^2]				Share of total area [%]				Drained area of total agricultural land [%]			
	SV		FAO		SV		FAO		SV		FAO	
	0–10 cm	**40–50 cm**	**0–10 cm**	**40–50 cm**	**0–10 cm**	**40–50 cm**	**0–10 cm**	**40–50 cm**	**0–10 cm**	**40–50 cm**	**0–10 cm**	**40–50 cm**
Very slow < 1.3	67	67	72	72	10	10	10	10	0.4	0.4	3	3
Slow 1.3–5	0	115	16	47	0	17	2	7	0	16.4	4.6	6.8
Moderately slow 5–20	309	36	96	2	44	5	14	0	47.1	0.7	8	0.1
Moderate 20–63	90	331	233	285	13	48	34	41	7.5	43.6	30.5	20.1
Moderately rapid 63–127	24	85	18	126	3	12	3	18	2.5	6.4	0.5	19.8
Rapid 127–250	6	6	113	20	1	1	16	3	0	0	21.1	4.1
Very rapid > 250	200	57	147	144	29	8	21	21	11	0.9	0.7	14.5
Water holding capacity[b] [mm 10 cm^{-1}]	**Area [km^2]**				**Share of total area [%]**				**Drained area of total agricultural land [%]**			
	SV		**SV**	**FAO**	**SV**		**FAO**		**SV**		**FAO**	
	0–10 cm	**40–50 cm**	**0–10 cm**	**40–50 cm**	**0–10 cm**	**40–50 cm**	**0–10 cm**	**40–50 cm**	**0–10 cm**	**40–50 cm**	**0–10 cm**	**40–50 cm**
0–20	66	304	214	308	9	44	31	44	0	41	25	38
20–40	571	283	438	305	82	41	63	44	65	24	42	30
40–60	30	108	13	53	4	16	2	8	4	4	2	1
60–80	29	1	30	30	4	0	4	4	0	0	0	0
80–100	0	0	0	0	0	0	0	0	0	0	0	0
Dry bulk density[c] [g cm^3]	**Area [km^2]**				**Share of total area [%]**				**Drained area of total agricultural land [%]**			
	SV		**FAO**		**SV**		**FAO**		**SV**		**FAO**	
	0–10 cm	**40–50 cm**	**0–10 cm**	**40–50 cm**	**0–10 cm**	**40–50 cm**	**0–10 cm**	**40–50 cm**	**0–10 cm**	**40–50 cm**	**0–10 cm**	**40–50 cm**
0 – 0.2	0	0	0	0	0	0	0	0	0	0	0	0
0.2 – 0.4	45	24	0	5	7	3	0	1	0	0	0	0
0.4 – 0.6	23	0	4	0	3	0	1	0	0	0	0	0
0.6 – 0.8	1	0	1	0	0	0	0	0	2	2	0	0
0.8– 1.0	88	0	88	0	13	0	13	0	0	0	0	0
1.0 – 1.2	43	5	66	45	6	1	10	7	7	7	6	0
1.2 – 1.4	304	113	260	25	44	16	37	4	42	42	30	4
1.4 – 1.6	62	337	236	434	9	48	34	62	6	6	31	41
1.6 – 1.8	120	99	31	153	17	14	4	22	10	10	0	23
1.8 – 2.0	0	23	0	23	0	3	0	3	0	0	0	0
2.0 – 2.2	0	0	0	0	0	0	0	0	0	0	0	0

Note: Area distribution of saturated hydraulic conductivity is presented after permeability class (a), water holding capacity (b) and dry bulk density (c) presented as the area distribution of the intervals 20 mm 10 cm^{-1}and 0.2 g cm^{-1}, respectively.

study. Furthermore, soil physical-, subsoil texture data and quantitative compilation on soil composition and soil physical parameters in forest and urban landscapes is lacking in quantification and resolution (Department of Forest Resource Management and Department of Soil and Environment, 2022).

Swedish textural point data has previously been shown to be too scattered for traditional interpolation methods in predicting soil texture for soil textural maps in Swedish landscapes (Djodjic et al., 2009). Also shown for the European dataset in LUCAS (Cordeiro et al., 2018). Additionally, Piikki and Söderström (2019) point to the increased errors of datasets with local- compared to national scales due to the availability of fewer calibration/validation samples. However, the development of pedotransfer functions adapted for Swedish soils have shown good fit regarding water content and porosity with the inclusion of soil organic carbon at a higher water content and bulk density linked to soil textural class (e.g., Kätterer et al., 2006). Furthermore, topsoil and subsoil textures have been shown to be overall correlated in Swedish soil profiles. At least in currently available soil samples (Sohlenius and Eriksson, 2009). However, to include subsoil characteristics in finer soil sampling, a grid is still required to develop robust regional pedotransfer functions. Leastways by the compilation of soil organic carbon and bulk density for deeper soil layers (Wösten et al., 2001), or by fitting pedotransfer functions based on a priori determination and sampling of most sensitive study area parameters (van Alphen et al., 2001). Overall, a lack of sampling of soil physical parameters, including soil structure and porosity, is a major gap to include in long-term soil monitoring. Especially since temporal changes of soil properties, such as hydraulic conductivity and soil organic carbon (Moberg, 2001), occur.

The spatial description of subsurface flow was improved by delineating fields with tile drainage plans from the economic map (Swedish Land Survey, n.d.). The new map, together with the soil hydrological dataset, can be of direct use for comparing drained and undrained fields and improve the water partitioning description. The drained arable land indicated a higher share of drainage on soils with higher clay content (Fig. 5) and a larger area of slow to moderate saturated hydraulic conductivity (Figure S2 Supplemental material). This is expected as we would anticipate a prioritization of fields with lower hydraulic conductivity as these fields are more susceptible to standing water. However, Table 4 indicates that drainage mainly occur in fields with moderate to rapid saturated hydraulic conductivity classes. This reflects that a major part of arable land is already drained, covering both less self-draining soils as well as soils with higher infiltration capacity.

The adjusted datasets under Sections 2.3.2 and 2.3.4 improved the spatial delineation of the water flow pathway (Fig. 6, Table 4 and Table 5). However, the effectiveness of tile drains remains unaccounted for. For example, nationally, 12.0% of all tile drainage in cropland was in need of maintenance in 2016. Additionally, 12.1% were considered to require the implementation of new drainage systems (SCB and Swedish Board of Agriculture, 2018). The rate of required maintenance of tile drained fields (exempting the requirement for implementing new

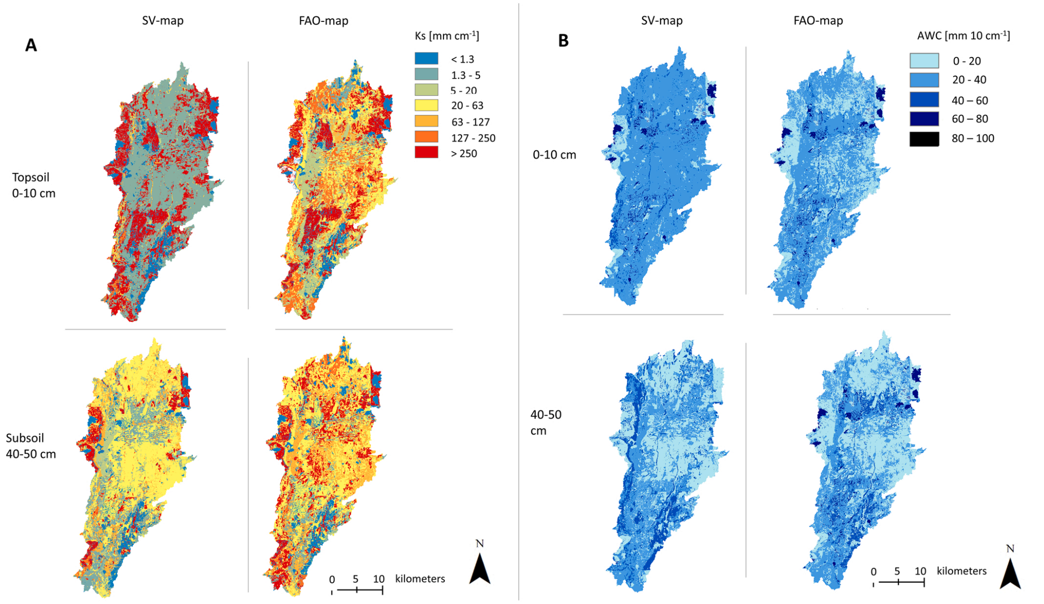

Fig. 4. Saturated hydraulic conductivity (Ks) [mm h^{-1}] (A) and water holding capacity (AWC) [mm mm^{-1}] (B) for Tidan catchment, SW Sweden. The Ks and AWC were mapped by combining point soil physical data with spatially distributed datasets of soil textural data. The left upper and lower maps in Fig. A and Fig. B respectively show Ks and AWC derived from soil textural maps classified by the Swedish soil texture system (SV-map). The right upper- nad lower maps in Fig. A and B show Ks and AWC derived from soil textural maps classified by FAO/USDA soil textural system (FAO-map). The upper maps show Ks (A) and AWC (B) for topsoil (0–10 cm soil depth). The lower maps show Ks (A) and AWC (B) for subsoil (40–50 cm).

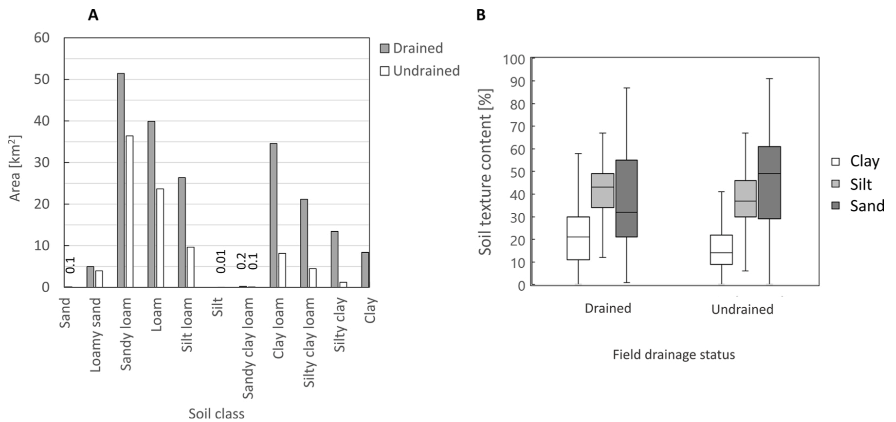

Fig. 5. Comparison of area per soil class with and without available tiled drainage plans (A) and soil texture content (percent clay, silt and sand respectively) for fields with and without available tile drainage plans (B) in Tidan catchment, Sw Sweden. The numbers above the bars for sand, silt and sandy clay loam in fig. A is the area written out for these soil classes.

drainage) has been estimated at 1–2% annually, in order to meet drainage requirements (Reiter and Bölenius, 2020). Thus, drainage capacity might be overestimated, as caused by estimations of the efficiency and effects of the national tile drainage network, or underestimated due to the expansion of newly drained fields. Comparing the ditch maps by Lidberg et al. (2021) (*DI*) with the manually delineated ditch maps produced by the County Administrative Board of Västra Götaland (2021) showed a change of ditches, likely representing a shift from surface drainage to subsurface drainage in later times (Jacks, 2019). There is a shortcoming in depicting the connectivity between ditches in the new main drainage map consisting of open ditches (Lidberg et al., 2021). This can possibly be explained by challenges in depicting subsurface

Table 5
Total length of existing detailed stream (STR)- and ditch maps (DI) compared to the new combined stream and ditch network based on the three individual datasets.

Nr	Product	Reference	Total length [km]
1	New hydrologic stream and ditch network[a]	This study, final product	**5350**
2	Natural streams	Ågren and Lidberg (2020)	4701
3	Ditches (AI)	Lidberg et al. (2021)	2423
4	Ditches (manually delineated)	County Administrative Board of Västra Götaland (2021)	774

Note: (**a**) is the new dataset derived from joining the below free-standing datasets (nr 2–4) where overlapping stream segments from nr 2 and 4, and stream segments from nr 2 overlapping agricultural fields have been erased.

pathways as culverts or poorly maintained ditches exposed to, e.g., the erosion of ditch banks.

The processing of data herein was done manually. We see a great potential for automation to shorten the processing time, for example by linking the processing steps and unify the in-data tables to a common format for use in common software handling spatial data. This is possible for all three datasets. The use of e.g. AI for constructing a model for point-to-pixel fitting of the soil data, to extend outside the dataset herein, is an appealing idea. However, such development would require larger independent dataset of soil physical properties for training and validating the model. This is a major limitation, as discussed in above sections. For the ditch- and stream network however, similar to the AI-model used by Lidberg et al. (2021), training a model for identifying "false" streams from the topographic stream network (Ågren and Lidberg, 2020) is a possibility for further exploration.

Automating the processing would additionally enhance the possibility to upscale the method to national level. This would be possible for both the soil datasets and the stream- and ditch network. Although the linking of soil physical properties data would reduce in spatial variation for northern Sweden, due to the absence of coverage from the digital soil map (Piikki and Söderström, 2019) in these areas. The methodology is simple and the possibility to extend outside Sweden is mainly linked to textural- and soil physical properties data available in other countries. Extracting the tile-drainage system based on the adjusted economic map is limited to Västra Götaland County, as we could not find similar dataset for other counties. However, the method of classification of line structures based on colour recognition is a simple and effective method for extracting linear features representing tile drains from maps of similar appearance from other regions. The extraction of waterbodies from satellite images or ortophotos is a concept used globally and the efficiency mainly dependent on image quality (e.g. reduced by cloud cover) and pixel resolution.

4.2. Implications of higher resolution spatial soil physical and hydrological functions datasets

The requirements of high spatio-temporal resolution depends on the research objective (Baffaut et al., 2015). Nevertheless, the increased availability of high resolution spatio-temporal data improves possibilities to study more complex questions when using models. For example, the inclusion of known subsurface flows in the Soil and Water Assessment Tool (SWAT) has been shown to improve water balance (Strömqvist et al., 2020; Rumph Frederiksen and Molina-Navarro, 2021;

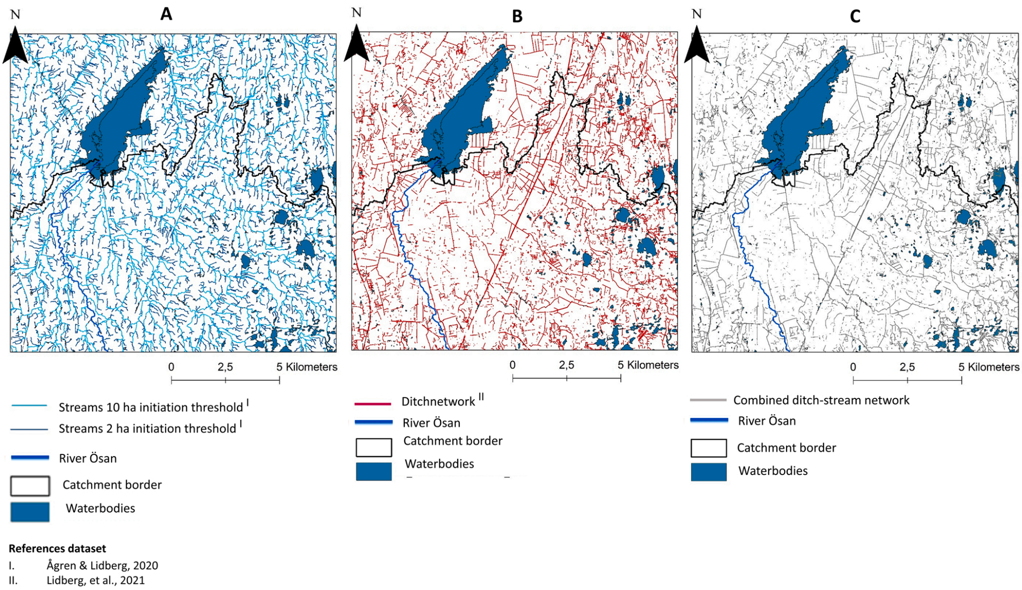

Fig. 6. Comparison of the delineation of the hydrological network in Tidan catchment where A shows streams delineated from topographic maps with stream initiation threshold of 2 ha (dark blue) and 10 ha (light blue) by Åberg & Lidberg (2020). The thicker dark blue stream depicts the river Ösan. Blue filled polygons represents lakes and wetlands. Fig. B delineates ditches (red) from Lidberg et al. (2021). Fig. C shows the new elaborated network from this paper, which is a joint network of the stream network (A), ditches (B), and additional ditches from the County Administrative Board of Västra Götaland (2021) and streams from Lindelöf (2021) where line segments overlapping each other-,and stream segment intersecting agricultural fields have been erased as "false" streams,.The black line in upper 3rd of the images shows the north border of Tidan catchment, and the lake is the south part of lake Östen. The image is an extraction (within 13.748 E; 58.595 N/14.065E; 58.401 N) from the larger Tidan sub-catchment.

Table 6
Comparison of area and volume of "missing"water bodies in Tidan catchment Sw Sweden, identified from ortophotos and satellite images, compared to available national datasets of open waters and wetlandss.

	Type[a]	Number	Area (km^2)	Estimated volume [m^3]	Numbers not included in readily available maps/ geospatial layers	Area (km^2)	Estimated volume [m^3]
Unique waterbodies	Reservoirs combined data	111	1.2	21.37 * 10^4	Reservoir 3	0.0011	0.111 * 10^4
	Ponds combined data	234	0.52	47.83 * 10^4	Ponds 2	0.00073	0.022 * 10^4
	Wetlands combined data	22	0.1	5.824 * 10^4	Wetland 1	0.0025	0.510 * 10^4
	Dams	6					
Original references	**Dataset[b]**	**Number of waterbodies**	**Total area [km^2]**	**Total volume [m^3]**	**Number of water bodies without statistics**		
	Meadow and Pasture Inventory	32	2.3	2735 * 10^4	5		
	Agricultural block database 2021	13	0.2	23.18 * 10^4	1		
	National Land Cover Database open wetlands	6088	12.5	2827 * 10^4	3930		
	Database of constructed wetlands	7	0.1	35.10 * 10^4	2		
	Swedish Water Archive waterbodies	10	0.4	286.7 * 10^4	5		

Note: Type (**a**) of water body were classified as reservoirs if they intersected with streams or ditches. Ponds were classified as open waterbodies if not intersecting with streams or ditches. Wetlands if they contained visible vegetation. Dams are constructed wetlands from the national database of constructed wetlands (SMHI, 2021. *Anlagda Våtmarker*. https://vattenwebb.smhi.se/wetlands/ accessed [2021–09-15]). *Nota bene: in the Swedish Water Archive, there are additional wetlands that could not be confirmed in their existence due to limitations of heavy vegetation cover such as forest and not identified* via *analysis of satellite data. These wetlands have not been included in the above calculated dataset on area and volume but should be considered if the total dataset is used for additional landscape analysis.*
Waterbodies in column Datasets (**b**) are the area and volume estimated from the original datasets. Note that the waterbodies overlap between the databases in some cases.

Valayamkunnath et al., 2022). Higher resolution in indata and parameters can furthermore reduce uncertainty for parameters known to be sensitive to model algorithms (see, e.g., Romanowicz et al., 2005; Veith et al., 2010; Arnold et al., 2012; Koo et al., 2020; Escamilla-Rivera et al., 2022). Additional details in temporal variation enables an improved description of short-term events, e.g., seasonal- or sub-daily effects. Although the impact of input data that is dependent on resolution, i.e., the aggregation of land units in e.g. hydrological response units (s.c. HRUs) and hydrological processes in models with a larger scale, might masks differences in the high spatial resolution of indata (e.g., Li et al., 2012). The same might not be valid for temporal effects, e.g., where hydrological response variation in a catchment is dependent on the spatial intra-catchment heterogeneity of both climate and land-soil properties (e.g., Jothityangkoon and Sivapalan, 2001). The changed distribution of weather extremes caused by climate change speed up hydrological process in field to landscape scales (Fischer and Knutti, 2014). Trends in the current climate indicate more extreme rainfall events (e.g., Grusson et al., 2021), and the synergetic effects of multiple weather events (so-called compound events) call for improved knowledge of landscape responses to various events and their interactions at local scale (Zscheischler et al., 2018). The change of pulse events will require new approaches in data collection and hydrological modelling; moreover, complementary studies at various scales are needed to understand the impacts and, e.g., design of mitigation measures (e.g., Garg et al., 2022). Furthermore, although data might be available at high spatial resolution, the temporal scale of input parameters for modelling short-term events might be too coarse to match the means, an issue to discuss, e.g., when linking landscape hydrology with short-term weather events.

The datasets presented herein mainly relate to surface waters. Nevertheless, considering retention to groundwater storages is equally important, with respect to both storage- and flow pathways in natural- and manmade (anthropogenic) water infrastructure. A limit from surface to subsurface flows from the dataset herein concerns the age of the economic map and the tile drainage plans it refers to, as well as the limited access to tile drainage plans for other areas. Further work is needed to highlight delineated subsurface flows and water outtake/return flows for anthropogenic use in agriculture, industry, households and other sectors. For example, the inclusion of irrigation outtake and re-routing in the catchment water balance can be important in achieving a better hydrological representation of anthropogenic landscapes (Strömqvist et al., 2020). Some of these data are accessible through the national statistical unit (SCB), yet limited due to secrecy (Strömqvist et al., 2020). Additionally, a model representation of connectivity between groundwater/surface waters in hydrological models is needed to accurately quantify hydrological pathways (Berghuijs et al., 2022). It has already been established that the dynamic representation of especially sub-soil hydrological flows for Swedish conditions is missing (Barthel et al., 2021).

4.3. Policy implications

Our new and improved datasets indicate the spatial complexity of both natural and manmade water infrastructure at catchment scale. This is critical information for accurate water balance under current and future water balance studies. As climate change accelerates, events and periods of both excess and scarcity of water increase in incidence and duration. Knowing the combined strengths of water infrastructure for partitioning, flows and storage will be critical at both local (e.g., field and farm) and catchment scale. The improved datasets can be used in the evaluation of landscape sensitivity to drought and flood events accounting for spatial heterogeneity. An accurate depiction of waterbodies and soil properties improves estimations of landscape water storage. Together with the improved ditch-stream network dataset, it might also improve knowledge on the connectivity of water storages and upstream-downstream effects of the surplus/deficiency of water throughout catchments. The datasets are a basis to inform and evaluate the synergetic effects of local adaptation measures at catchment scale. The analysis and data collection in this paper clarify that additional effort would be of value to tile drainage data linked to field levels, in order to incorporate accurate field bound drainage capacity at a catchment scale, as well as coupling with effects on the subsurface level.

Despite increased possibilities for data collection by, e.g., reduced costs and improved automation for the in-situ collection of spatio-temporal data, there are paradoxical signs that data availability as open source becomes more limited and less monitored (Harris et al., 2020; Thorslund and van Vliet, 2020; SMHI, 2022a; b). Hence, paradoxically, the number of suggestions/method developments of incorporating effects of soil structure dynamics in soil-crop systems caused by biological activity, e.g., at the plot- and centennial-decennial scale (e.g., Meurer et al., 2020) and in intra-annual fluctuations in soil porosity (e.g., Chandrasekhar et al., 2018) and vegetation (e.g., Thompson et al., 2011), increase the demand for soil data sampling intervals both spatially and temporarily. According to some, the increase of openly available RS data, the development of various innovative ways of processing and data mining of various landscape parameters reduces direct dependency on in-situ sampling (e.g., Cui et al., 2021; Duethmann et al., 2022; Fuentes et al., 2022; Xue et al., 2022; Yan et al., 2022). However, in this work we show the more remote data products that are available – the more it paradoxically enhances the importance of having accurate in-situ datasets for thorough, independent validation (e.g., Cosh et al., 2004; Weerasinghe et al., 2020; Gelebo et al., 2022). Thus, a thorough campaign of support from national and regional funders, as well as land owners and local populations that enables in-situ sampling for verification is still on the agenda. This should possibly be synced or incorporated in any research programme for improving remote access data on landscape parameters to match the means.

5. Conclusions

In this study, we have developed the information of soil physical characteristics, natural and manmade water flow as well as storage at catchment scale to improve water balance partitioning and the description of landscape (catchment) hydrology. We show that with available soil texture data, improved with point measured soil physical properties, key landscape hydrological functions such as soil water holding capacity and saturated soil hydraulic conductivity, change significantly. Further, the explicit addition of tile drainage and merged natural and manmade ditch networks increases flow pathways significantly. Finally, the catchment water storage was comparatively well understood in available/existing data.

To secure water under climate change, water allocation will increase in importance for many water users at catchment scale, including safeguarding environmental flows alongside human supplies and agricultural needs. The use of more complex models and the improved model performance of hydrological processes need to better capture both natural parts and the impact of anthropogenic structures and processes concerning the hydrological cycle at landscape scale linked to both surface and subsurface (unsaturated soil) water flows. Improved soil physical properties and merged water flow paths and storage, distributed accurately, will be as equally important as climate input for these water balances estimates. This calls for the long-term increased/maintained data collection of essential landscape-, hydrological, climate parameters with the evaluation of sampling size and interval (spatial and temporal) for, at a minimum, calibration/validation purposes. In addition, transparency of access for available data linked to water outtake/recharge/storage is needed to be able to evaluate and follow up any landscape measures affecting landscape hydrological storage capacity.

CRediT authorship contribution statement

Louise Malmquist: Methodology, Investigation, Formal analysis, Validation, Visualization, Data curation, Writing – original draft. **Jennie Barron:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2023.108304.

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Crop production depends on water availability from precipitation and soil infiltration and storage. Historically, efforts to enhance soil moisture have focused on modifying agricultural landscapes and hydrological pathways. With climate change increasing water saturation and deficit risks, understanding the role of water diversion and storage in sustaining crop yields is crucial. This thesis explored how the water balance in Swedish agricultural landscapes can be affected by climate change and historical, current, and potential future agricultural water management and anthropogenic interventions.

Louise Malmquist received her graduation at the Department of Soil and Environment at the Swedish University of Agricultural Sciences. She received her Degree of Master of Science in Agriculture from the same university.

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