



HAL
open science

Influence of climate change on water partitioning in agricultural watersheds: Examples from Sweden

Youen Grusson, Ingrid Wesström, Elina Svedberg, Abraham Joel

► **To cite this version:**

Youen Grusson, Ingrid Wesström, Elina Svedberg, Abraham Joel. Influence of climate change on water partitioning in agricultural watersheds: Examples from Sweden. *Agricultural Water Management*, 2021, 249, pp.106766. <10.1016/j.agwat.2021.106766>. <hal-04082898>

HAL Id: hal-04082898

<https://hal.science/hal-04082898v1>

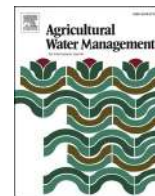
Submitted on 26 Apr 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization



Influence of climate change on water partitioning in agricultural watersheds: Examples from Sweden

Youen Grusson^{*}, Ingrid Wesström, Elina Svedberg, Abraham Joel

Dept. of Soil and Environment, Swedish University of Agricultural Sciences, P.O. Box 7014, SE-750 07 Uppsala, Sweden

ARTICLE INFO

Handling Editor - Dr Z Xiyang

Keywords:

Climate change
Agro-hydrology
Runoff
Water distribution
SWAT modeling

ABSTRACT

Future climate change is predicted to increase precipitation volume in Sweden, and also to modify precipitation patterns and produce more intense rainfall events. This study examined the impact of such changes in three small Swedish watersheds dominated by agricultural land. The Soil and Water Assessment Tool (SWAT) was used to investigate the relationship between changes in precipitation (monthly and daily) and monthly water partitioning between runoff, soil water content, and evapotranspiration. A climate ensemble produced from Representative Concentration Pathway (RCP) scenarios 4.5 and 8.5 and five different global climate models, regionalized by the Swedish regional climate model RCA4, was used to feed the SWAT model. The results showed similar outcomes for the three sites, with an increase in total monthly precipitation often associated with an increase in high daily rainfall events. Increased intensity of rainfall, particularly events > 15 mm/day, was associated with an increase in runoff, but not in soil water content. In the few cases where monthly precipitation decreased, soil water content also decreased. The main impact on all hydrological components of the system appeared to be more significant during the middle of the cropping season (May–August) than at the beginning (April) or end (September). These conclusions emerge despite the climate model ensemble underestimating the heaviest daily rainfall events. Overall, this study showed that the projected increasing trend in seasonal rainfall in southern Sweden would not result in more soil water being available for crop production.

1. Introduction

The occurrence of global climate change during the past century is now widely accepted by the scientific community and is expected to continue in the future (Cook et al., 2016). Among other effects, climate change is modifying the pathway of water within the hydrological cycle and the distribution of water in the landscape (Grusson et al., 2018; Hartmann et al., 2013; Held and Soden, 2006; Jiménez Cisneros et al., 2014). Climate change has been shown to impact e.g., soil water (Destouni and Verrot, 2014; Verrot and Destouni, 2016), evapotranspiration (McCabe and Wolock, 2015), and discharge (Milly et al., 2005; Roudier et al., 2015). These impacts are suggested to be strongly linked to changes in local precipitation and temperature patterns (Putnam and Broecker, 2017; Stagge et al., 2015; Vautard et al., 2013). When rainwater reaches the soil surface, there is an initial partitioning between surface runoff and infiltration. Any change in the frequency and intensity of rainfall can potentially influence the partitioning between these components. A change in the volume of infiltrating water will influence soil moisture content and evapotranspiration rate (Jung et al.,

2010; Verrot and Destouni, 2016). The partitioning of rainwater between surface runoff and soil water is a key process from an agronomic perspective because of its direct relationship with available soil water content, plant transpiration, and biomass production (Ben-Gal et al., 2003; Hanks and Rasmussen, 1982; Hillel and Guron., 1973; Kirkham, 2005; Shani et al., 2007). Understanding how the rainfall pattern will change under expected climate change and the impact on hydrological components is crucial for future adaptation of agriculture. Many studies have investigated the impact of climate change on discharge (often considered as “water availability”) (e.g. Alfieri et al., 2015; Koutroulis et al., 2018; Lobanova et al., 2018). Substantially fewer studies have examined other hydrological component (e.g. Gädeke et al., 2017; Grusson et al., 2018; Verrot and Destouni, 2016), and even fewer have focused specifically on surface runoff/infiltration partitioning following changes in precipitation intensity.

The impact of climate change on Nordic agriculture is complex. For instance, the region could benefit from climate change through an extension of the cropping season and possibilities for growing new crops, but negative effects such as new pests and diseases are expected to

^{*} Corresponding author.

E-mail address: youen.grusson@slu.se (Y. Grusson).

<https://doi.org/10.1016/j.agwat.2021.106766>

Received 13 November 2020; Received in revised form 14 January 2021; Accepted 19 January 2021

Available online 16 February 2021

0378-3774/© 2021 The Author(s).

Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

counterbalance such positive effects (Maracchi et al., 2005; Olesen and Bindi, 2002; Olesen et al., 2011; Peltonen-Sainio et al., 2009; Uleberg et al., 2014; Wiréhn, 2018). This fine balance between positive and negative impacts of changes in precipitation pattern needs to be assessed. In Northern Europe as a whole, future precipitation is projected to increase on average (Jacob et al., 2014; Strandberg et al., 2015). This increase could be positive in countries where irrigation is not widely used by farmers, e.g., in Sweden, cultivation mostly depends on natural rainfall and only 1.7% of agricultural land is irrigated (EuroSTAT, 2016). However, an increase in precipitation at seasonal scale is likely to be combined with an increase in heavy daily rainfall events (Jacob et al., 2014; Strandberg et al., 2015), and thus much of the additional rainfall may be lost as runoff. In addition, if more precipitation falls on fewer days during the season, the overall increase in seasonal precipitation could be detrimental and cause longer dry periods or excess water in some periods. Adaptation of Nordic agricultural systems appears to be necessary, and is actually already ongoing (Juhola et al., 2017).

Climate adaptation must be designed for local or at most regional level. Local studies with an agro-hydrological focus must therefore be conducted. A relatively limited number of studies have investigated the relationship between modifications to water pathways induced by climate change and the impacts on Nordic agriculture. In a systemic review of Nordic agriculture under climate change, Wiréhn (2018) located only 35 peer-reviewed papers, most relating climate variables directly to crop yield and plant phenology (Eckersten et al., 2012; Kristensen et al., 2011; Olesen, 2005; Ozturk et al., 2017; Pulatov et al., 2015) or to system vulnerability (Juhola et al., 2017; Kvalvik et al., 2011), without studying the rainfall-soil water relationship or the impact of rainfall frequency on agro-hydrological systems. In a rare exception, Patil et al. (2010) investigated the effects of changes in average rainfall volume and number of rainy days on soil water content in a rainfall-controlled system of lysimeters. They concluded that changes in the total amount of rainfall or in the number of rainy days had no significant impact on maize yield or soil water regime, but also pointed out limitations of their experimental design. A report in Sweden on the impact of more frequent extreme climate events on crop yield found that for the period 1965–2014, most years with low yield were associated with above-average dry or wet periods (De Toro et al., 2015).

To understand the impact of climate change on the water cycle and the consequences for agriculture, it is necessary to i) analyze how precipitation will change during the upcoming century and assess the level of confidence in climate projections for the study region; and ii) investigate the impact of those changes on rainwater partitioning. In a novel approach, the present study considered both these aspects, with the aim of providing an integrated picture of the rainfall-soil water-runoff nexus and extending the assessment of climate change impacts on Swedish agriculture.

In the first part of the study, the climate projections available for Sweden were evaluated from an agro-hydrological perspective, complemented by an analysis of rainfall variations (total volume and precipitation intensity patterns) for different regions of Sweden. The second part of the study consisted of hydrological modeling, using the Soil and Water Assessment Tool (SWAT), of possible correlations between changes in precipitation regime and the water distribution at the soil surface. The SWAT model (Arnold et al., 1993) has been widely used around the world in recent decades and has been shown to produce satisfactory results in modeling most components of the hydrological cycle (Douglas-Mankin et al., 2010; Gassman et al., 2002, 2007, 2014). It has been used previously to assess the impact of climate change on the hydrological cycle (Grusson et al., 2018; Pascual et al., 2014; Zhang et al., 2015). Despite some limitations, SWAT has been shown to provide reasonably good representations of the volume of surface and subsurface runoff (Ahmadi et al., 2019; Cheng et al., 2016; Qi et al., 2020; Zhang et al., 2019).

Specific objectives of this study were to i) perform a comprehensive

study including evaluation of available climate datasets, projected changes in rainfall intensity and total volume, and a SWAT-based impacts assessment on water partitioning; and ii) assess how projected future increases in total precipitation and changes in precipitation patterns in agricultural regions of Sweden might affect the actual water distribution in agricultural areas. The latter is critical knowledge when developing adaptation strategies to mitigate the effects of climate change on agriculture, e.g., irrigation planning during the cropping season. It was obtained by investigating the relationship between daily and monthly precipitation data and the monthly distribution of water at three sites in southern Sweden.

2. Materials and methods

2.1. Study sites

The three sites selected for the study were small agriculture-dominated watersheds in southern Sweden (Fig. 1), where most Swedish agricultural production is concentrated (Peltonen-Sainio et al., 2015). These watersheds were chosen to represent different agro-climatic zones in southern Sweden, but also the regional differences in projected precipitation. This latter is expected to differ slightly between the extreme south of Sweden (Skåne; light precipitation increase), the south-east (Östergötland; moderate precipitation increase), and the south-west (Västergötland; greater precipitation increase) (Eklund et al., 2015).

The area of the watersheds ranges from 590 ha (Östergötland) to 931 ha (Västergötland), and all show a relatively low variation in elevation (Fig. 1). As a consequence of this rather limited size and slope of the watersheds, the hydrological network investigated consisted largely of artificial agricultural ditches.

Crop production is the dominant land use at the Västergötland and Skåne sites, covering 90% of all land uses in both watersheds. At the Östergötland site, 52% of the watershed is given over to crops (values for 2012), but substantial areas are also dedicated to pasture (20%) or forest (26%), especially in headwater areas. The crops grown are mainly cereal (wheat, barley, oats) and sugar beet (Fig. 2).

Soil type differs between the watersheds. Västergötland is dominated (95%) by a deep clay soil (clay content > 40% in first 20 cm; > 50% in 20–100 cm layer, ~ 60% below 100 cm depth). Skåne is predominantly (82%) covered with relatively shallow soils (60 cm) dominated by a sandy texture (45–60% sand). Östergötland has a more complex and wide soil diversity, with about 45% of the surface covered by clay-dominated soil (45–75% clay), but also with substantial areas of loamy soil (45–70% loam, 26% of total watershed area) and sandy soil (83–100% sand, 26% of total watershed area). More details on soil data processing for the model can be found in Section 2.2.2, while detailed soil profiles for each watershed are presented in Tables S1–S3 in Supplementary Material (SM).

There are also differences between the sites regards rainfall regime during the cropping season (April–September) (Fig. 3). At the Östergötland site, precipitation increases during the first two months of the season, peaks in July, and then decreases for the remainder of the season. At the two other sites, cropping season precipitation peaks in August and then decreases slowly for the remainder of the season (Västergötland) or stays rather stable (Skåne). As a result of this difference in regime, mean annual precipitation (1961–2000) in Skåne (685 mm) is 15% higher than in Östergötland (585 mm) and 6% higher than in Västergötland (645 mm). In terms of temperature, the three sites experience similar conditions during the cropping season, with daily temperature ranging from 10 °C to 20 °C.

2.2. Hydrological simulation

2.2.1. SWAT model

The Soil and Water Assessment Tool (SWAT) was used in this study to

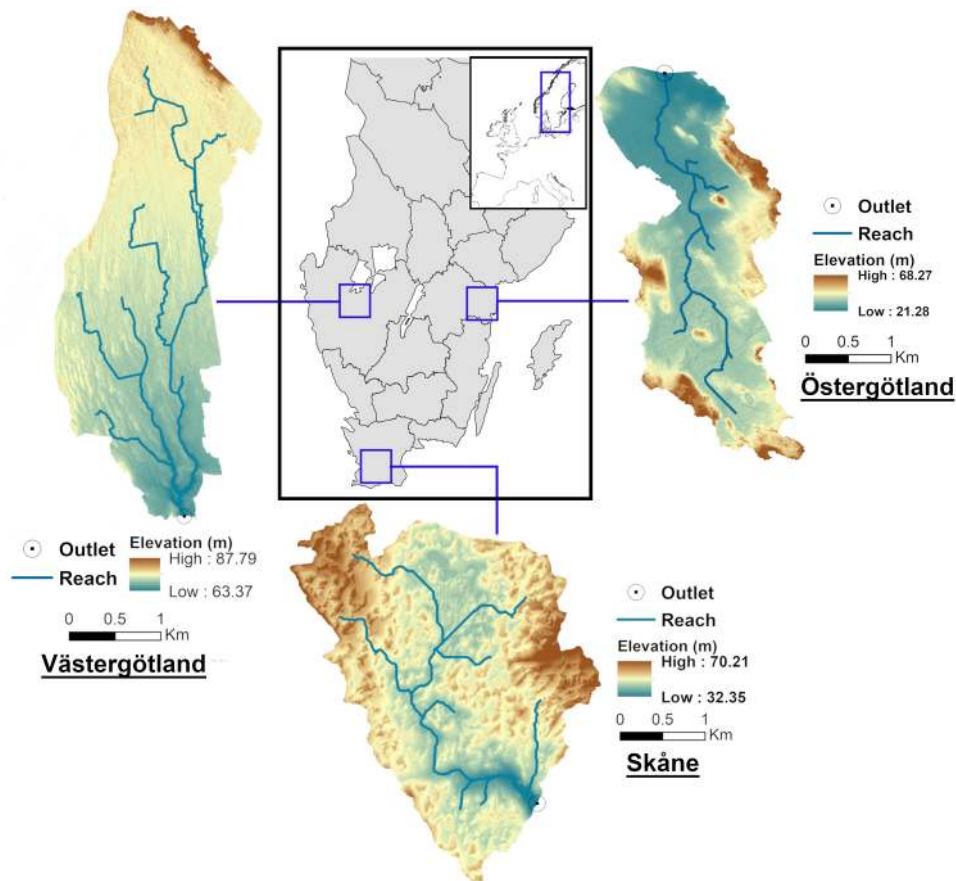


Fig. 1. Location and topography of the Västergötland, Skåne, Östergötland study sites in southern Sweden.

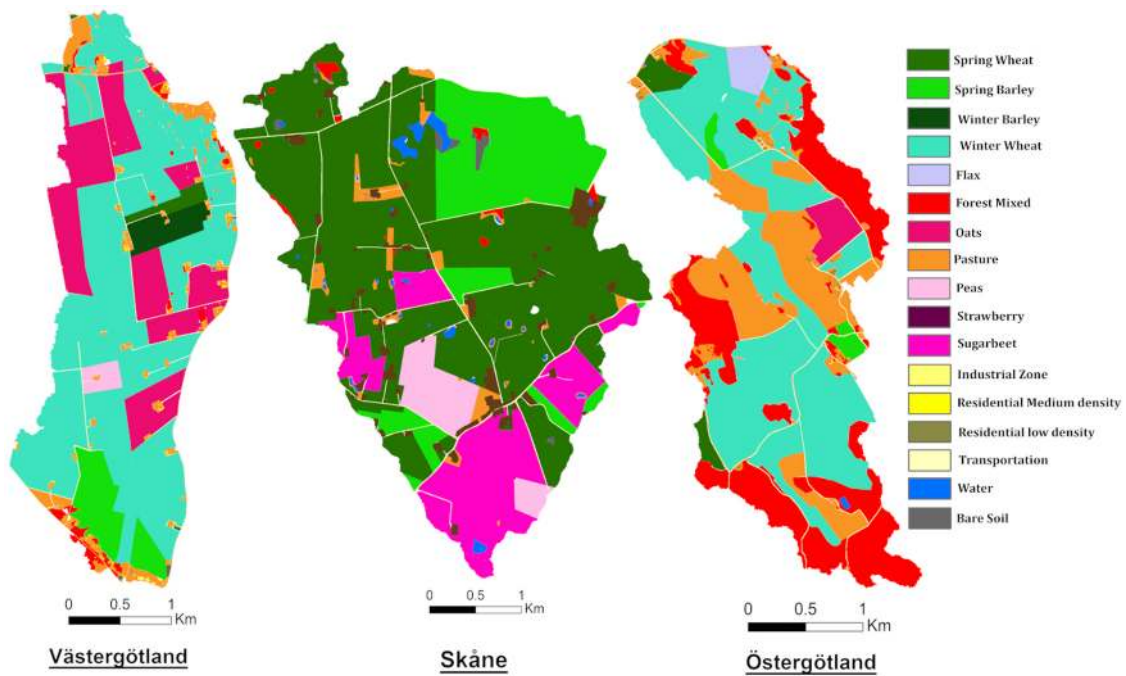


Fig. 2. Land use in the Västergötland, Skåne, and Östergötland watersheds in 2012.

investigate the relationship between changes in precipitation volume, rainfall distribution, and water distribution within the hydrological system at monthly time steps. SWAT is an agro-hydrological semi-

distributed model based on a first discretization of landscape according to stream network and topography (Arnold et al., 1993). This information is used to divide the watershed into sub-watersheds (Arnold et al.,

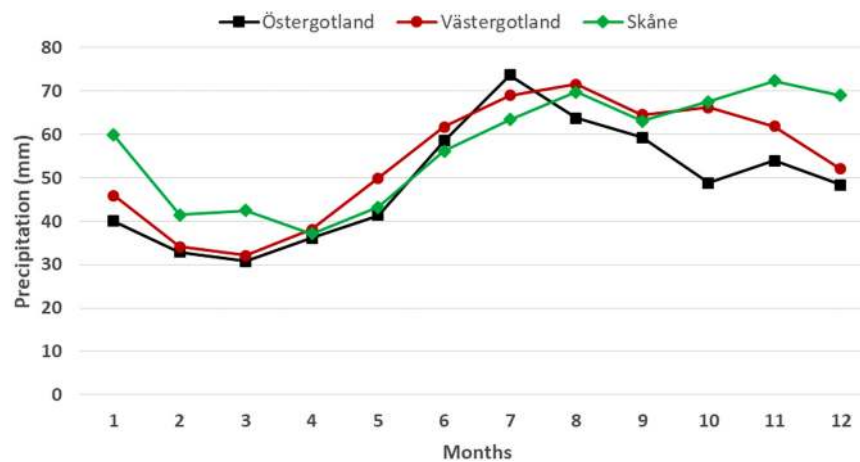


Fig. 3. Mean monthly rainfall at the three study sites in the period 1961–2015.

1993, 1998; Neitsch et al., 2011). Hydrological response units (HRUs), i. e., homogeneous areas of soil, land cover, and slope, are then identified within each sub-watershed. Water balance is computed within each HRU, articulated around four compartments (snow, soil, shallow aquifer, deep aquifer) linked by hydrological processes such as infiltration, surface runoff, subsurface runoff, evapotranspiration and percolation. More details about the processes modeled by SWAT can be found in the theoretical documentation (Neitsch et al., 2011). Computation is performed at HRU level, aggregated at sub-watershed level, and routed from upstream to the final outlet. A GIS-based graphical interface helps users define HRUs and generate associated input files; here we used ArcSWAT 2012 (Olivera et al., 2006).

2.2.2. Input data for SWAT and model set-up

The selected sites are part of the Swedish national environmental monitoring program (Naturvårdsverket/SLU; www.slu.se/en/environment) and are therefore well-documented, with substantial amounts of relevant data available. The topographical map presented in Fig. 1 originated from a 2 m resolution digital elevation model (DEM) provided by the Swedish Mapping, Cadastral and Land Registration Authority (Lantmäteriet; www.lantmateriet.se).

Several sources were combined to describe the soils in each watershed. These were: i) soil maps from the Swedish Geological Institute (SGU; www.sgu.se), including dominant soil parent material at 50 cm depth, ii) soil profile descriptions from the Swedish University of Agricultural Sciences (SLU), including physical properties of agricultural soils (Wiklert et al., 1983), and iii) analytical data on soil characteristics (including texture and organic carbon) from the Swedish national environmental monitoring program. The soil map from SGU shows the geographical distribution of parent material in the selected watersheds, but contains no information about soil texture or other soil physical parameters. Each parent material in the soil map was associated to a soil profile and to a set of soil analytical data from the national monitoring program. The three sources of information were converted to a raster with 2 m resolution, to match the DEM. Brief descriptions of the dominant soil types are given in Section 2.1. More details of physical parameters of each profile used as input to the SWAT model can be found in Tables S1–S3 in SM.

Agricultural land use data were obtained by combining regional maps of agricultural land produced by the Swedish Board of Agriculture (<https://nya.jordbruksverket.se>) with corresponding tables on crop production. Spatial land use information for 2012 was used to perform the modeling, but the 2000, 2012, and 2015 maps were compared to ensure that no major changes had occurred within the watersheds in this period. The crop tables give an account of agricultural practices and crops grown in each watershed in different years. It was assumed that

the most common crop reported by farmers was the dominant land use inside each polygon of the GIS map. Forests, urban areas, and water bodies were identified from the cadastral plan and orthophotos provided by Lantmäteriet. Following the resolution of the DEM, a land use raster with resolution 2 m was created by merging the different sources of information.

The SWAT default database (Arnold et al., 2012a) was used to link land use information from the map to vegetation growth. Data on a few minor crops grown within the study areas were not available in the model databases, so these were classified as closely related crops. For instance, some low vegetable row crops were classified with ground cover corresponding to strawberries (STRW). The default values in the SWAT model of heat units needed for each crop to develop and reach maturity were modified to overcome problems linked to day length at northerly latitudes. Median dates for sowing and harvesting in each watershed were taken from Berglund et al. (2002), who compiled data from Statistics Sweden (1987–93) and experiments at SLU. The grazing season was set as April 1–October 31, based on Swedish Board of Agriculture (2016). In order to simulate forest and forest areas with stable biomass, an initial biomass was set for each simulation year. Thus each simulation year started (1 January) with an initial biomass of 100 tonnes per hectare, allowed to grow during the summer. Fertilization regime was kept in automatic mode (SWAT default mode), with inputs applied when soil nutrient conditions generated stress and reduced crop development.

Observed weather data for the past 50 years (1970–2018) were taken from the closest weather station to each watershed. These stations, which were selected from the Swedish Meteorological and Hydrological database (SMHI; www.smhi.se/data), were *Sturup*, *Skövde*, and *Norrköping1* for Skåne, Västergötland, and Östergötland, respectively. Daily temperature and precipitation data from those stations were used to calibrate and validate the SWAT model.

A projected climate dataset was also obtained from SMHI. This dataset originated from projections made with an ensemble of global circulation models (GCMs) in the Euro-Cordex project (Jacob et al., 2014), dynamically-downscaled on a 5 km grid over Scandinavia via the SMHI regional climate model (RCM) RCA4. The dataset was then corrected against the SMHI re-analysis product MESAN (Häggmark et al., 2000), using a data-based scaling algorithm from SMHI (Yang et al., 2010). Five GCM-RCM pairs were used together with two representative concentration pathway (RCP) scenarios, RCP 4.5 and RCP 8.5, created by the Intergovernmental Panel on Climate Change (IPCC). These scenarios represent possible future radiative forcing in the atmosphere, where RCP 4.5 assumes that greenhouse gas emissions are progressively regulated over the coming century to reach stability by 2100, while RCP 8.5 assumes increasing greenhouse gas emissions over time at the

current rate (Detlef et al., 2011; Moss et al., 2010). For each model, an “historical period” starting in 1970 is available to enable comparisons with actual observed data. For each site, the closest point of the grid to the field was considered. Only temperature and precipitation data are available in this dataset. Table 1 presents more details of the projected climate data used in this study.

The SWAT model offers several methods for computing evapotranspiration. Because only precipitation and temperature data were available in the projected climate dataset, the Hargreaves method (Hargreaves and Samani, 1985) was selected in this study to simulate evapotranspiration. A comparison was made of the Hargreaves method and the FAO-recommended Penman–Monteith method over the reference period (1971–2000), and very strong correlations ($R^2 \approx 0.95$) between the methods were obtained for all sites (see Fig. S1 in SM).

Data on discharge at the outlet of each catchment were also needed to calibrate the modeling framework. Data series of mean monthly discharge were obtained from the Swedish national environmental monitoring program.

2.2.3. Calibration and validation

Identification of sensitive parameters in the SWAT model and model calibration were performed using SWAT-Cup (Abbaspour, 2013), an external tool that allows SWAT users to perform automatic calibrations using different algorithms (Arnold et al., 2012b). In this study, we selected the SUFI-2 algorithm (Abbaspour et al., 2004), because of its ability to identify an appropriate set of parameter values in a limited number of iterations (Yang et al., 2008). Calibration through the SUFI-2 algorithm aims at identifying values for the defined set of sensitive parameters, in order to optimize the values of the Nash–Sutcliffe efficiency (NSE) criterion (Nash and Sutcliffe, 1970). Calibration was performed through 1500 runs, as recommended by Yang et al. (2008). Calibration and validation were performed at monthly time steps, over 10- or 11-year periods.

The NSE is a normalized metric comparing the variance of the observed dataset with the variance of the observation and simulation residual errors. The value of NSE ranges from $-\infty$ to 1 and it is very sensitive to errors in higher values. An NSE value of 0 indicates that the model is as accurate as the mean of the observations, a value higher than 0.5 is considered to indicate satisfactory performance, and a value of 1 indicates a perfect fit.

Other metrics used to assess model performance were NSE calculated on the root square (NSEsqrt) and on the logarithm of the discharge values (NSElog). NSEsqrt reduces the influence of errors in peak values on the metric, while NSElog reflects the influence of errors in low-flow simulations (Oudin et al., 2006; Seiller et al., 2012, 2017). Percentage bias (Pbias), which gives information on the deviation in average volume between simulated and observed values, was also calculated. Its value ranges from 0 to $\pm \infty$, with positive values indicating overestimation and negative values indicating underestimation. A value of \pm

20% is usually considered an acceptable limit. Finally, coefficient of determination (R^2), with values ranging from -1 to 1 , was computed. An R^2 value higher than 0.60 was considered satisfactory. More details on the criteria values showing goodness of fit in hydrological modeling can be found in Moriasi et al. (2007).

2.3. Evaluation of the climate ensemble

The available climate dataset for this study was first assessed by comparison against observed dataset for the historical period 1971–2000. This was done by plotting cumulative distribution functions (CDFs) to compare the different distributions of data over the period. Two different CDFs were considered, for total monthly rainfall and daily rainfall. For both, a separate analysis was conducted for each month of the cropping season, to assess how accurately the local climate was depicted by the climate ensemble at monthly and daily scale.

2.4. Future rainfall regime

From an agricultural perspective, the distribution of daily rainfall events is as important as the overall amount of monthly precipitation. An analysis was therefore made of changes in the temporal distribution and frequency of monthly and daily rainfall. Observed data for 1971–2000 were compared against the projected climate in two different future periods of the climate ensemble: 2021–2050 and 2051–2080.

In a first step, the change in total monthly precipitation between past and future periods was investigated. The significance of the difference was tested using a Wilcoxon rank-sum test, a non-parametric hypothesis test challenging the similarity of two independent distributions. It tests the null hypothesis that both distributions are equal against the alternative hypothesis that one distribution is stochastically different from the other (Mann and Whitney, 1947). The difference between the distributions is deemed significant at $p < 0.05$. This test was performed with the inbuilt Matlab function *RankSum*.

In a second step, the frequencies of daily rainfall events were calculated for each 1 mm interval and plotted for each month of the cropping season, where frequency was defined as the number of events of a class divided by the total number of events. To simplify the daily frequency-intensity representation, the five climate models for each scenario were pooled to a single distribution, allowing comparison of the entire climate ensemble for each scenario/period against the observations.

A Wilcoxon rank-sum test could not be conducted for each of the previously defined 1-mm classes, so thresholds of > 1 , > 15 , and > 30 mm were selected to test whether the number of days with rainfall exceeding those thresholds differed significantly. In an agro-hydrological context, daily rainfall of < 1 mm can be considered inadequate for agriculture, because the water would evaporate before

Table 1
Global climate model (GCM) and regional climate model (RCM) data available for the two representative concentration pathway (RCP) scenarios considered in this study.

Short name	GCM	RCM	Correction	Start	End
Scenario RCP 4.5					
RCP45-Model 1	CNRM-CERFACS-CNRM-CM5	SMHI-RCA4	MESAN-1989–2010	1/1/1970	12/31/2100
RCP45-Model 2	ICHEC-EC-EARTH	SMHI-RCA4	MESAN-1989–2010	1/1/1970	12/31/2100
RCP45-Model 3	IPSL-IPSL-CM5A-MR	SMHI-RCA4	MESAN-1989–2010	1/1/1970	12/31/2100
RCP45-Model 4	MOHC-HadGEM2-ES	SMHI-RCA4	MESAN-1989–2010	1/1/1970	11/30/2099
RCP45-Model 5	MPI-M-MPI-ESM-LR	SMHI-RCA4	MESAN-1989–2010	1/1/1970	12/31/2100
Scenario RCP 8.5					
RCP85-Model 1	CNRM-CERFACS-CNRM-CM5	SMHI-RCA4	MESAN-1989–2010	1/1/1970	12/31/2100
RCP85-Model 2	ICHEC-EC-EARTH	SMHI-RCA4	MESAN-1989–2010	1/1/1970	12/31/2100
RCP85-Model 3	IPSL-IPSL-CM5A-MR	SMHI-RCA4	MESAN-1989–2010	1/1/1970	12/31/2100
RCP85-Model 4	MOHC-HadGEM2-ES	SMHI-RCA4	MESAN-1989–2010	1/1/1970	12/30/2099
RCP85-Model 5	MPI-M-MPI-ESM-LR	SMHI-RCA4	MESAN-1989–2010	1/1/1970	12/31/2100

reaching the root zone (Dastane and FAO, 1974). However, the threshold for efficient rainfall that actually supplies water to crops may differ significantly depending on a large number of parameters (e.g. type of crop, temperature, crop development stage). For this reason, thresholds of > 15 and > 30 mm/day, chosen from local frequency-intensity rainfall characteristics, were considered in this study. Again, a pooled distribution of all five models per scenario was used to perform the test.

2.5. Impact of rainfall changes on surface water distribution

The output of the SWAT model for the three different sites was processed to evaluate changes in partitioning of rainfall between the different pathways (runoff, infiltration) in the local hydrological systems following changes in the rainfall regime, at monthly and daily time steps. The aim was to identify the impact of changes in the rainfall regime on surface fluxes in the hydrological cycle. In this study, surface and subsurface runoff from SWAT output were combined as 'runoff' to characterize the "fast pathway", in contrast with the "slow pathway" (infiltration-groundwater-groundwater recharge).

In a first step, runoff as a percentage of total precipitation was compared for past and future periods, to evaluate changes in the fraction of surface water quickly flushed out of the watershed over time. A histogram was plotted of this fraction of runoff for observed data and for each model/period/scenario. Again the periods 2021–2050 and 2051–2080 were compared with the baseline period 1971–2000.

In a second step, a statistical Wilcoxon rank sum test was used to determine the significance of differences in monthly volume of runoff water and in soil water content between the historical period and the two projected periods.

3. Results

3.1. Evaluation of the climate ensemble

Comparison of the CDFs for the monthly-observed data and the data generated by the climate ensemble over the historical period 1971–2000 indicated that the climate ensemble fairly accurately represented local monthly rainfall conditions at the three sites (Fig. 4). However, the climate ensemble tended to slightly overestimate the monthly volume of precipitation for the Skåne site, particularly from May to August. Similar overestimation was observed for June and July at the Västergötland site, and for May at Östergötland. A recurrent bias was observed also for the highest part (90–100%) of the distribution, where several members of the ensemble seemed to overestimate the monthly precipitation. Thus the climate ensemble reasonably simulated the volumes of monthly precipitation at the three sites. A similar analysis was performed to assess the distribution of daily rainfall events (Fig. 5). The results showed that the climate ensemble provided a good representation of the observed distribution, with very few divergences between the different models of the climate ensemble, especially for low values of daily rainfall. However, in this case the very highest part of the distribution of observed daily rainfall events was not described by the climate ensemble distribution for all sites, indicating that the climate ensemble underestimated extreme daily rainfall.

In the present study, emphasis was placed on local evaluation of precipitation. The spatial homogeneity and the relatively slow temporal variation in temperature in a region of agricultural plains makes it easy to capture by climate models. Precipitation is a more difficult parameter to spatialize and downscale, considering its more local and stochastic

nature. For this reason, temperature is better described by climate models than precipitation, as shown for instance in the assessment of the EuroCORDEX ensemble conducted by Kotlarski et al. (2014). Based on that publication and on a report on Sweden prepared by Eklund et al. (2015) using the same dataset as in this study, temperature is considered to be depicted satisfactorily by the ensemble and can be expected to rise at all sites during the cropping season (Eklund et al., 2015).

3.2. Future rainfall regime

3.2.1. Monthly precipitation

The Wilcoxon rank sum tests on total monthly precipitation for each site and each period revealed several significant trends between the observed historical period and the projected period (Table 2). There was an increase in precipitation volume in May at all three sites, especially in scenario RCP 8.5. Two of the sites also showed an increasing trend in precipitation volume in June and August. In April, precipitation volume increased only in scenario RCP 8.5 at the end of the century, while in September some scenarios showed a decreasing volume. The middle of the cropping season (May–August) appeared to be more strongly impacted by the projected change in monthly precipitation volume.

3.2.2. Daily rainfall frequencies

The rainfall analysis was then scaled down to investigate the changes projected at daily time steps. Fig. 6 shows the frequencies of different daily rainfall intensity classes for each site, offering a general view of their distribution for each scenario in the reference period (1971–2000) compared with the projected periods 2021–2050 and 2051–2080.

The overall observation was that, regardless of site or month, days with precipitation > 30 mm were more frequent in the projected periods than in the historical period. However, this difference was only valid up to a certain daily rainfall intensity, since the few extreme values of daily rain intensity observed during the historical period were always higher than those produced by the climate models for the future periods. The only notable exceptions, for which the climate model returned higher extreme values of daily precipitation, were for the month of April at Skåne and Västergötland, and the month of July at Östergötland. An increase in the frequency of the last intensity rainfall class in the projected climate data was also seen in almost all cases. This particular trend was not visible within the historical dataset and seems too regular and repetitive to depict a natural pattern. The bias correction applied to the climate data, aiming to reduce outliers, is likely to have affected the highest values of the projected distribution, and could explain the lower extreme values and the increase in frequency for the last intensity class simulated by the models.

The results of Wilcoxon rank-sum tests on the rainfall frequency-intensity findings are summed up in Table 3.

As it would have been too complicated to carry out a test for each daily rainfall intensity class illustrated in Fig. 6, a decision was made to focus on the number of days with rainfall volume > 1 mm, > 15 mm, and > 30 mm. As found for the total monthly volume of precipitation (Table 2), an increasing trend was more apparent during the middle of the cropping season. April showed stable values, and September showed a decreasing trend. This pattern changed when the daily intensity threshold was increased. The number of days with precipitation > 15 mm increased in April, especially at the Västergötland site, for which all scenarios/periods indicated such a trend. On the other hand, a decreasing trend in September was only detected in one case at Västergötland. When considering number of days with precipitation

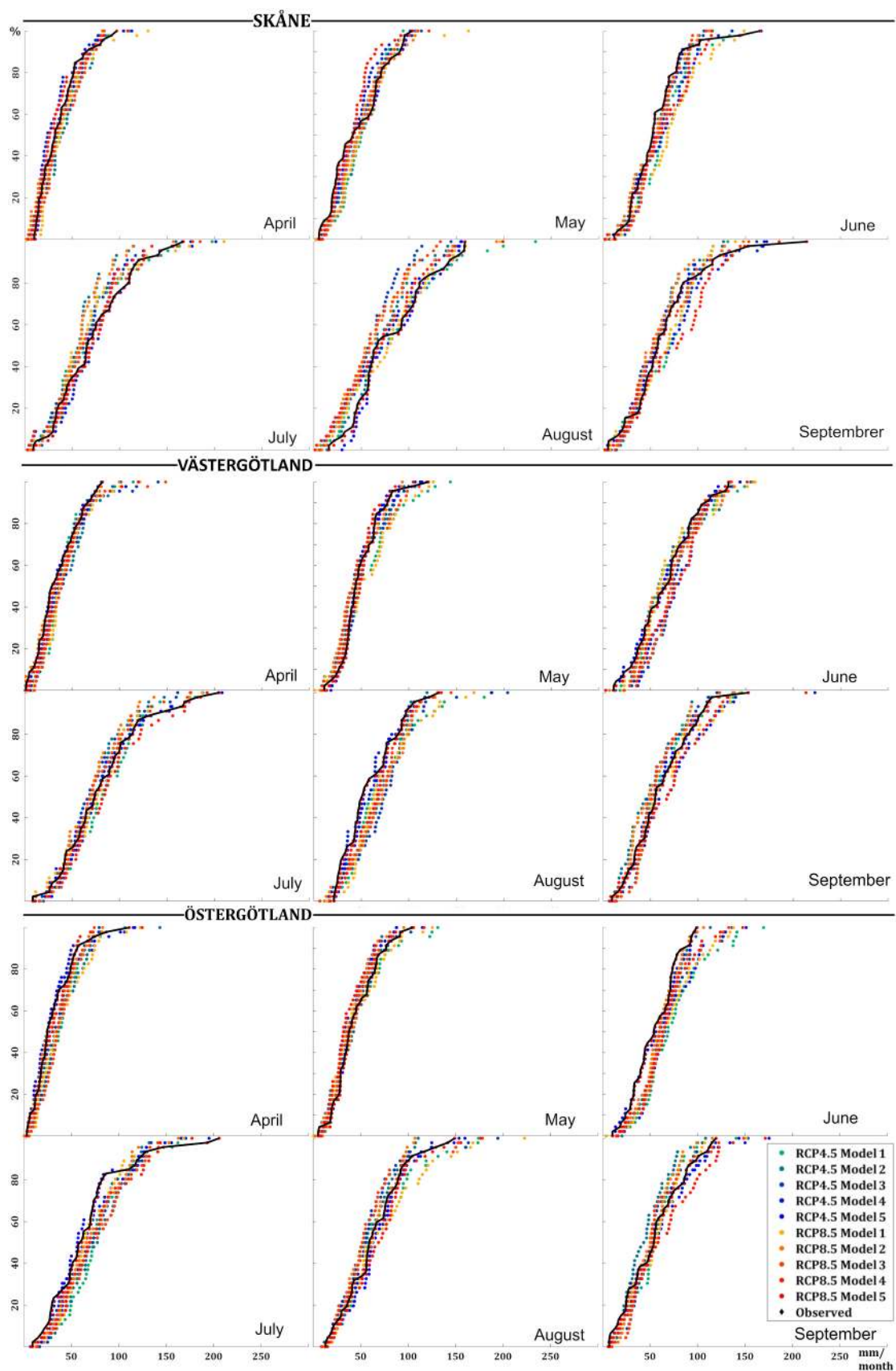


Fig. 4. Cumulative distribution functions (in %) of monthly precipitation at Skåne, Västergötland, and Östergötland for the observed dataset and each of the climate models in the historical period 1971–2000.

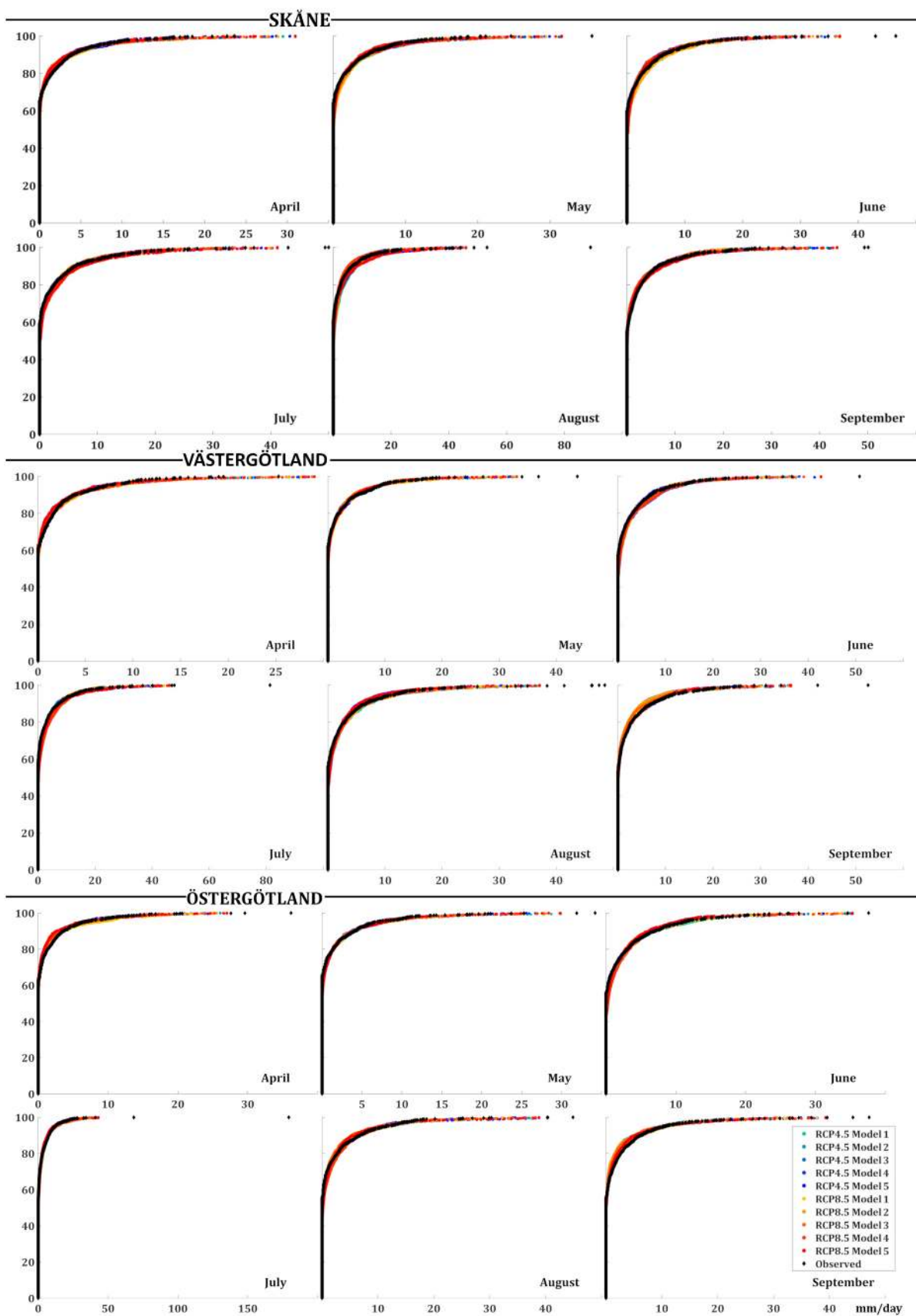


Fig. 5. Cumulative distribution functions (in %) of daily precipitation at Skåne, Västergötland, and Östergötland for the observed dataset and each of the climate models in the historical period 1971–2000.

Table 2

Wilcoxon rank sum test p-values for projected monthly precipitation relative to the historical period 1971–2000 at Skåne, Västergötland, and Östergötland sites. Significant trends ($p < 0.05$) are colored, with green cells indicating a positive trend and orange cells a negative trend. Empty cells indicate no significant trend.

Period	Total monthly precipitation											
	2021-2051		2051-2080		2021-2051		2051-2080		2021-2051		2051-2080	
RCP	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5
	Skåne				Västergötland				Östergötland			
April				0.01				0.02				
May	0.01	<0.01	<0.01	<0.01		0.04		0.03		<0.01	0.02	<0.01
June	0.02	0.02		0.02	<0.01	0.01	0.03	0.01				
July					<0.01	<0.01	<0.01	<0.01				
Aug.	0.01	0.01	<0.01	0.02					0.03	0.04	0.01	0.03
Sept.					0.03		0.01	0.02	0.03	0.01	0.01	0.04

> 30 mm, the differences between sites were more distinct. At the Skåne site, there was an overall increase during the season, with the exception of July. At the Västergötland site, the increasing trend during mid-season seen for the two previous thresholds was again evident. The Östergötland site showed a clear decrease in the number of days with > 30 mm rainfall in the two first months of the season, followed by a clear increase during the rest of the season.

3.3. Hydrological simulations

3.3.1. SWAT model performance

The performance of the SWAT models deployed for the three sites is shown in Table 4. Following the classification of Moriasi et al. (2007), the NSE values obtained showed calibration performance ranging from good at Östergötland to very good at Västergötland and Skåne. For validation, the NSE values decreased slightly, but still ranged from acceptable (Östergötland) to very good (Skåne).

These values indicate accurate simulation of the hydrological dynamics and peak values by the different SWAT models. The values of NSE_{sqr} ranged from good to very good and the values of R^2 were always higher than 0.65, which can also be considered to indicate good model performance. The Pbias values ranged from very good to satisfactory for Östergötland in validation and for Västergötland in calibration, and supported the evaluation based on NSE. The scores were lower for NSE_{log}, indicating that low-flow periods were less easily captured by the models, especially in Östergötland. For Västergötland, the validation was conducted over a two-part period because additional discharge data (from 96 to 00) became available after the calibration process, but the values of the different metrics were not influenced by the use of a split period. Hydrographs of the calibration and validation periods for each of the three sites revealed that discharge volumes within the three systems were quite low (Fig. 7).

This partly explains the limited performance of the model in reproducing low flows (NSE_{log}), as small differences in very small values had a strong impact on the value of the metrics. However, the models seemed to capture the annual discharge dynamics accurately, as they indicated peak flow around January and February, and a decrease in water level to a minimum in July or August. Only one seasonal peak was clearly not captured by the model, that at Västergötland in January 2011. It is important to note that seasonal peak flow was not included within our study period, as our analysis focused on the cropping season (April to September), corresponding to the decreasing and low flow periods, which both seemed to be fairly well simulated by the model (Fig. 7).

In order to evaluate the accuracy of the discharge simulations and the likelihood of the hydrological system simulated by the model, the

monthly volume of each hydrological component in the reference period 1971–2000 was plotted (Fig. 8). The hydrological balance appeared to be reasonable and the graphs revealed several interesting findings on the hydrological functioning of the different watersheds. In April, the precipitation input barely covered evapotranspiration and soil water content in all three watersheds declined to meet the evapotranspirative demand. During the period April-May, shallow aquifers made a substantial contribution to stream flow, but their contribution then declined during the rest of the season. This is consistent with the decreasing water level in aquifers during summer and their disconnection from the surface network consisting mainly of shallow ditches.

The importance of subsurface runoff compared with surface runoff also differed between the watersheds. Subsurface runoff exceeded surface runoff at Östergötland and Skåne, while at Västergötland these two components were relatively well balanced but surface runoff volume was slightly greater. This is consistent with the high clay content of the Västergötland soil compared with that at the other two sites. The distribution of water between surface and subsurface runoff is consistent with the very low slope of the watersheds, but also with the presence of agricultural drainage systems. These were not explicitly integrated into the modeling framework, but were indirectly included by reinforcement of the subsurface water pathway within the modeling environment through calibration of soil physical parameters (see Tables S4 and S5 in SM).

3.4. Impact of rainfall changes on surface water distribution

Following analysis of the rainfall distribution, the output from the calibrated SWAT models was examined for each of the three sites and for the three datasets (historical from observed data (1971–2000) and projected from climate models (2021–2050 and 2051–2080)), in order to assess how rainfall input was partitioned by the agro-hydrological SWAT model.

The monthly ratio between water received by the system from precipitation and water flowing out of the system through the fast hydrological path is presented in Fig. 9. Different trends can be seen for the different sites. In April, there was a marked negative trend in runoff/rainfall ratio at the Östergötland and Västergötland sites. The Västergötland site had a relatively stable ratio from past to future for the rest of the cropping season, with a slight increase during June and August. The Östergötland site continued to show a decreasing trend during May, and then an increase in the ratio during June and July. In contrast to both these sites, Skåne showed an increasing trend in the ratio from the start of the season (April) that continued during most of the season, but was most obvious in May, August, and September.

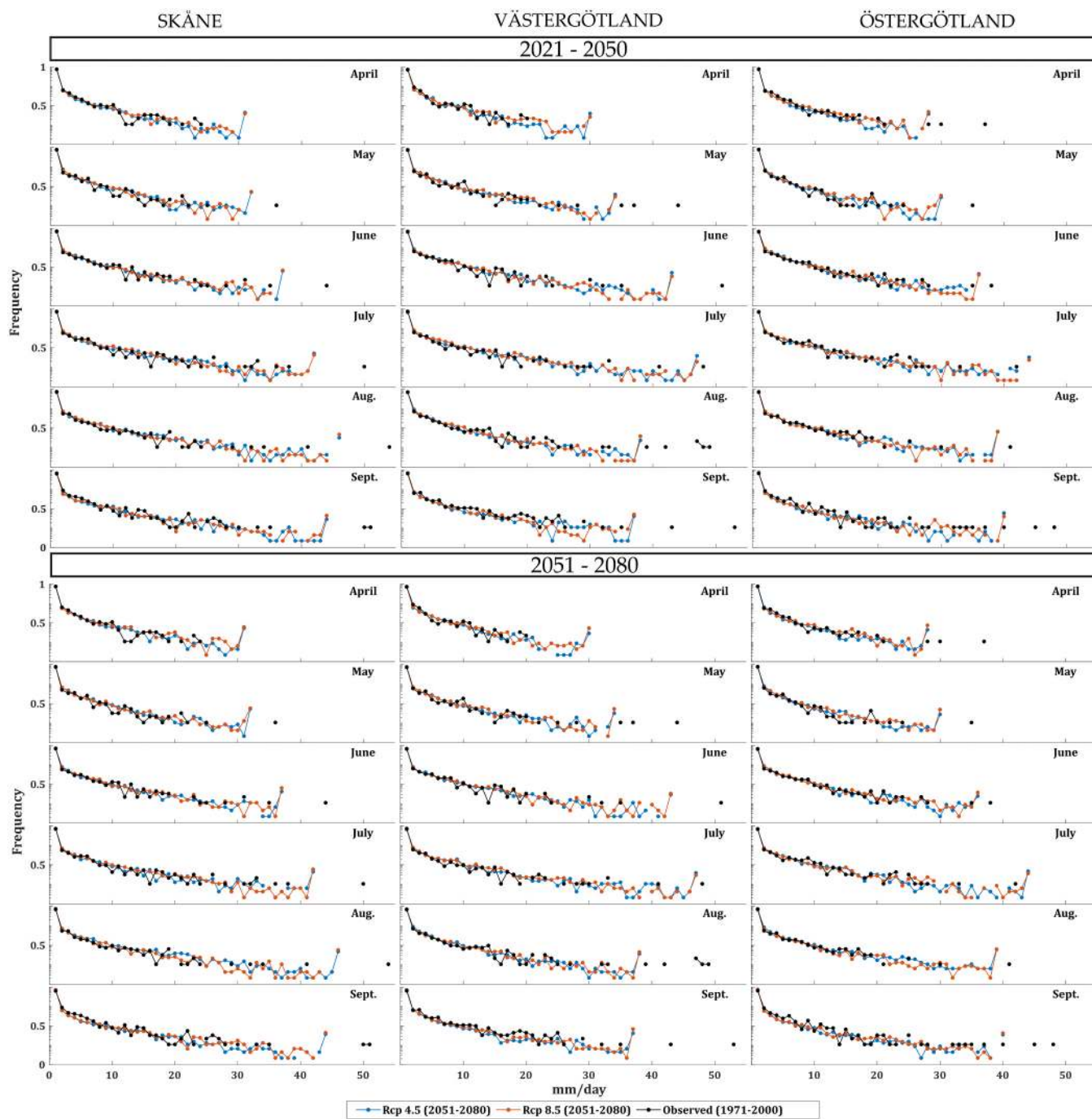


Fig. 6. Monthly rainfall frequency-intensity diagram comparing observed data with the climate ensemble data for each scenario in the reference period (1971–2000) and the projected periods (2021–2050 and 2051–2080).

Table 3

Wilcoxon rank sum test p-values for projected number of days with rainfall > 1 mm, > 15 mm, and > 30 mm relative to the historical period 1971–2000 at the Skåne, Västergötland, and Östergötland sites. Significant trends (p < 0.05) are colored, with green cells indicating a positive trend and orange cells a negative trend. Empty cells indicate no significant trend.

Period	Daily rainfall>1mm				Daily rainfall >15mm				Daily rainfall>30mm			
	2021-2051		2051-2080		2021-2051		2051-2080		2021-2051		2051-2080	
RCP	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5
Skåne												
April							0.01		0.02	0.04	0.02	0.01
May	0.01	<0.01	0.01	0.01	0.04		0.02	0.01	0.03	0.04	0.04	0.02
June	0.04	0.04	0.04		0.04	0.01	0.02	0.01	0.04	0.04		0.04
July		0.03		0.03								
Aug.	0.03	0.01	<0.01	0.04	0.04	0.04	0.01	0.05		0.04	0.02	0.04
Sept.		<0.01	0.01	0.03					0.04	0.03		0.02
Västergötland												
April					0.01	<0.01	0.02	0.01				
May	0.04	0.03		0.04								
June	0.01	0.02		0.04	0.02	0.04		0.02	0.01	0.04		0.02
July	<0.01	<0.01	<0.01	<0.01	0.01	0.01	0.04	<0.01	0.01	0.04	0.03	
Aug.			0.03									
Sept.	0.04	0.04	<0.01	0.04			0.04					
Östergötland												
April							0.01		0.01	0.01	0.01	0.01
May		0.03	0.03	0.03		0.02		0.03	0.01	0.01	0.01	0.01
June		0.03							0.04		0.04	0.04
July		0.04							0.02	0.04	0.04	
Aug.			0.03		0.03		0.01	0.01	<0.01	<0.01	<0.01	<0.01
Sept.	<0.01	<0.01	<0.01	<0.01								

Table 4

Calibration and validation performance at monthly time steps of the Soil and Water Assessment Tool (SWAT) model for the three study sites.

		Period	NSE	NSELog	NSEsqrt	R ²	Pbias
Östergötland	Calibration	95–04	0.74	0.47	0.67	0.74	2.32
	Validation	05–15	0.59	0.24	0.51	0.65	21.93
Västergötland	Calibration	01–10	0.76	0.66	0.77	0.81	17.86
	Validation	96–00 & 11–15	0.68	0.54	0.7	0.7	5.25
Skåne	Calibration	95–04	0.92	0.56	0.84	0.93	–12.53
	Validation	05–15	0.77	0.62	0.79	0.78	10.98

A Wilcoxon test was performed on the output of the different calibrated SWAT models regarding the monthly volume of runoff, soil water content, and actual evapotranspiration (AET) for each site, period, and scenario (Table 5). As in the previous analysis, the results showed a pattern of runoff changes during the cropping season. During mid-season the runoff volume increased more significantly, whereas at the beginning (April) and end (September) of the season it was relatively stable (Skåne) or decreasing (Östergötland).

No similar pattern in soil water content was observed during the cropping season and this hydrological reservoir seemed to be less impacted by climate change than runoff, with less significant trends. There was a clear difference in soil water content between the three sites, with that at the Skåne site remaining quite stable, that at Västergötland showing a rather uniform decreasing trend in June, July, and September, and that at Östergötland decreasing at the beginning and end of the season (April and September), but with an increase in May. The changes in evapotranspirative flux were similar for the Skåne and Västergötland sites, at which AET increased significantly from April to August in all scenarios and periods. In September, only the RCP 8.5 scenario gave an increase in AET. On the other hand, the Östergötland site showed very few variations in AET, with a significant increase only in April and even a decreasing trend in May for the RCP 4.5 scenario, with the rest of the cropping season showing quite stable

evapotranspiration (Table 5).

3.5. Overall impact of future climate on hydrological interactions

The variations in all meteorological and hydrological indicators investigated are summarized in Table 6. In the Wilcoxon tests, a trend was reported if at least three cases (scenarios/periods) showed a similar trend. Table 6 visualizes the links between different components of the hydrological cycle.

First, an increase in the number of days with precipitation > 15 or > 30 mm seemed to be linked to an increase in total monthly precipitation in all except five cases (Skåne April and September; Västergötland April; Östergötland June and July). In only one case, the number of days with > 30 mm rainfall decreased and the volume of monthly precipitation increased (Östergötland May).

Second, the number of days with > 30 mm rainfall seemed to be linked to the runoff/rainfall ratio. Of the 10 cases where the number of days with > 30 mm rainfall increased significantly, eight were associated with a similar trend in runoff/rainfall ratio. In several cases, the variation in those two components was also associated with an increase in other rainfall indicators, including total precipitation (e.g., Västergötland June, Skåne May). In other cases, the variation in number of days with > 30 mm rainfall and in runoff/rainfall ratio were the only

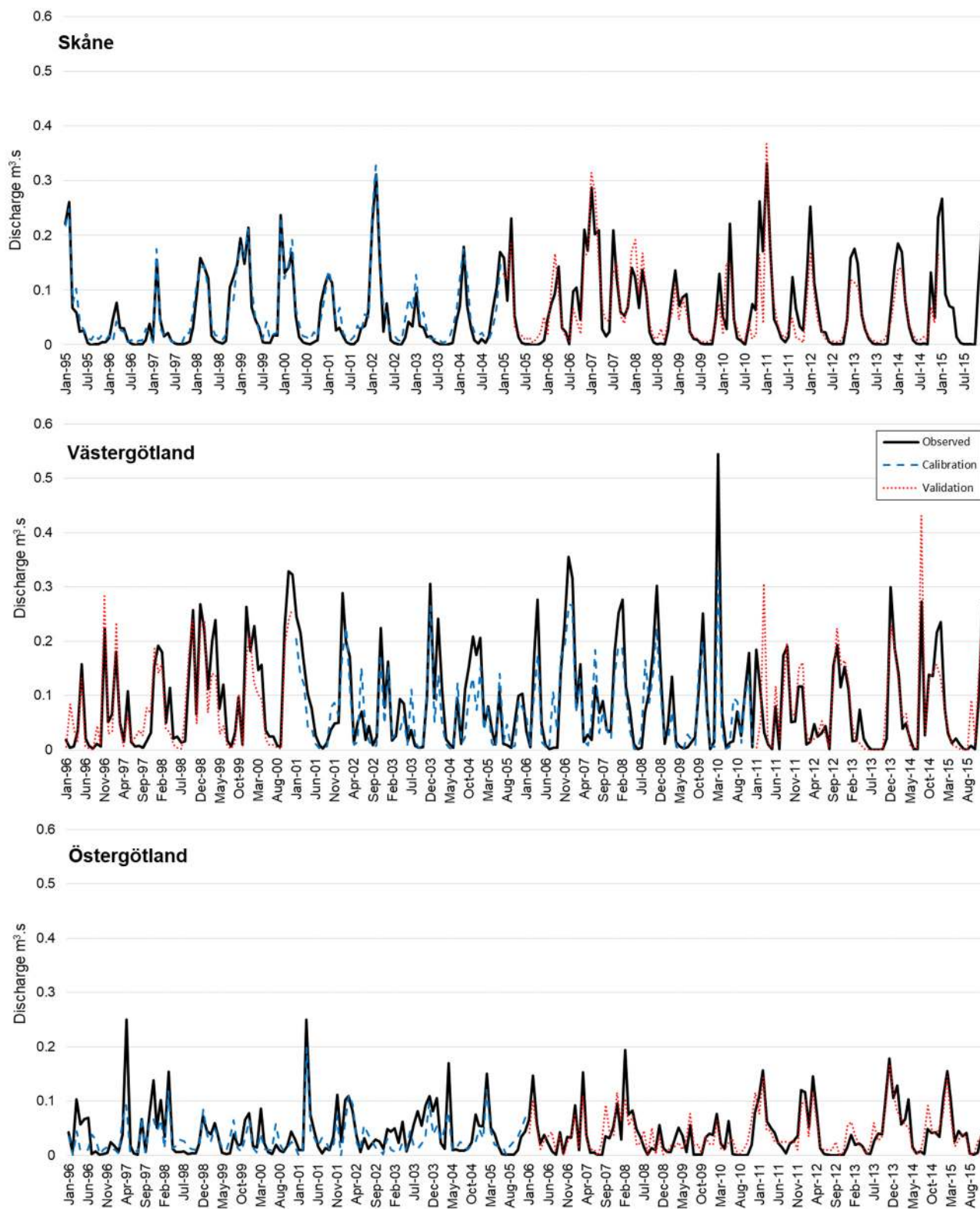


Fig. 7. Monthly hydrographs for the Skåne, Västergötland, and Östergötland watersheds in the calibration and validation periods.

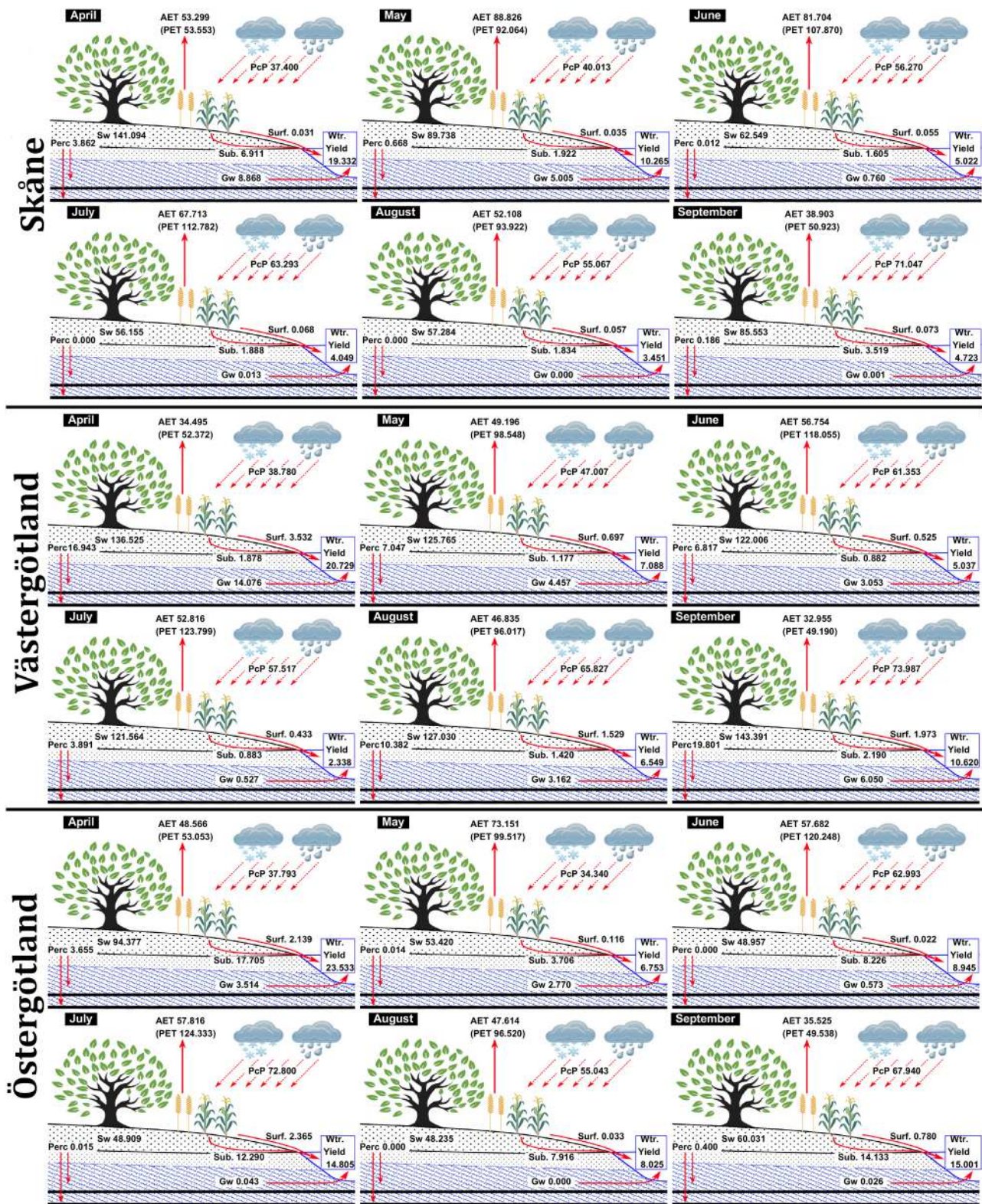


Fig. 8. Average monthly volume of hydrological components in the reference period (1971–2000) at Skåne, Västergötland, and Östergötland: precipitation (PcP), potential and actual evapotranspiration (PET – AET), soil water (Sw) surface runoff (Surf.), subsurface runoff (Sub.), percolation to aquifers (Perc.), shallow aquifer to stream (Gw), and water Yield (Wtr. Yield).



Fig. 9. Runoff as a percentage of total precipitation at the Skåne, Västergötland, and Östergötland sites. For each scenario, the five histograms represent the five different climate models as listed in Table 2. Note difference in vertical scale for Västergötland.

Table 5

Wilcoxon rank sum test p-values for projected runoff volume and soil water content relative to the historical period 1971–2000 at the study sites. Significant trends ($p < 0.05$) are colored, with green cells indicating a positive trend and orange cells a negative trend. Empty cells indicate no significant trend.

Period	Runoff volume				Soil water content				Actual evapotranspiration			
	2021-2050		2051-2080		2021-2050		2051-2080		2021-2050		2051-2080	
RCP	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5
Skåne												
April									<0.01	<0.01	<0.01	<0.01
May	0.02	0.02	0.03	0.02				0.03	0.02	<0.01	<0.01	<0.01
June	0.01	0.01	0.02	0.01				0.01	0.01	<0.01	<0.01	<0.01
July									<0.01	<0.01	<0.01	<0.01
Aug.	0.01	0.01	<0.01	0.02					<0.01	<0.01	<0.01	<0.01
Sept.										0.04		0.04
Västergötland												
April									<0.01	<0.01	<0.01	<0.01
May									<0.01	<0.01	<0.01	<0.01
June	0.01	0.02	0.05	<0.01	0.01	0.01		0.03	<0.01	<0.01	0.02	<0.01
July	<0.01	<0.01	<0.01	<0.01	0.03	0.01		0.02	<0.01	<0.01	<0.01	<0.01
Aug.									0.02	<0.01	<0.01	<0.01
Sept.	0.01		0.01		<0.01	0.04	<0.01			0.04		<0.01
Östergötland												
April	<0.01	<0.01	<0.01	0.03	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
May				<0.01	0.04		0.04	0.03	0.02		0.01	
June		0.01	0.04	0.03								
July												
Aug.	0.04		0.03	0.04							0.01	
Sept.	0.04		0.02	0.03	<0.01		0.01	0.03				

Table 6

Summary of results for monthly and daily rainfall indicators, runoff indicators, and soil water content at the Skåne, Västergötland, and Östergötland sites during the cropping season (April–September).

	Monthly rainfall	Daily Rainfall higher than			Runoff Ratio	Runoff volume	Soil water content	AET
		1mm	15mm	30mm				
Skåne								
April				+	+			+
May	+	+	+	+	+	+		+
June	+	+	+	+		+	+	+
July								+
August	+	+	+	+	+	+		+
Sept.		-		+	+			
Västergötland								
April			+		-			+
May	+	+						+
June	+	+	+	+	+	+	-	+
July	+	+	+	+		+	-	+
August					+			+
Sept.		-					-	
Östergötland								
April				-	-	-	-	+
May	+	+		-	-		-	
June		+		+	+	+		
July		+		+	+			
August	+		+	+		+		
Sept.	-	-			+	+	-	

trends visible (Skåne April, Östergötland June), or were even in contradiction to other rainfall indicators (Skåne September, Östergötland May). This reflects the relationship between heavy rainfall events and high runoff.

Third, an increase in monthly rainfall was not correlated with an increase in soil water content. Of the seven cases in which the total volume of monthly precipitation increased, only one (Östergötland May) also showed an increase in soil water content. In other cases, an increase in monthly rainfall was accompanied by a clear increase in several daily rainfall indicators, but no change in soil water volume (Skåne May and August, Östergötland June and July) or even a decreasing trend (Västergötland June and July). On the other hand, a decrease in monthly precipitation and days with rainfall > 1 mm was linked to a decrease in soil water content (Västergötland and Östergötland September).

Fourth, the stable to decreasing trend in soil water content despite increasing precipitation was also related to an increase in AET for two of the three sites (Skåne and Västergötland). For the Östergötland site, the lack of increase in soil water content was not related to an increase in AET except in April, when a decreasing amount of soil water and runoff seemed to be associated with increased AET.

4. Discussion

This study investigated the impacts of changes in total monthly rainfall volume and in daily rainfall frequency-intensity on agro-hydrological systems in three small-scale agricultural watersheds in Sweden. The agro-hydrological model SWAT was set up for the three watersheds. This model has been shown to be an efficient tool for simulating hydrological fluxes in the unsaturated zone, such as surface and subsurface runoff, evapotranspiration, and soil moisture (Douglas-Mankin et al., 2010; Gassman et al., 2002, 2007, 2014). The partitioning of rainwater reaching the ground is computed by the USDA-SCS curve number (CN) method (SCS, 1986) modified by Williams (1995). This is one of the most widely used methods to compute runoff volume (Beven, 2011) and is known to produce a fair representation of the runoff generated (Sahu et al., 2012; Yen et al., 2015). It was deemed

suitable for our study watersheds, where the conditions are close to those for which the SCS method was developed (small watershed, rapid hydrological response, dominated by agricultural land, situated in a humid to sub-humid climate zone) (Beven, 2011). In addition, during calibration of the SWAT model, CN values are calibrated differently for each HRU, reducing the area to which a particular value of CN is applied and increasing the efficiency of the method (Hawkins, 2014; Hawkins et al., 2009).

The calibration and validation procedure conducted for each of the three models showed good ability of the models to describe discharge at the watershed outlet, with performance criteria mainly indicating good to very good model performance based on Moriasi et al. (2007). The model deployed at the three sites was calibrated on discharge, which in SWAT is an aggregate of rapid fluxes (surface and subsurface runoff) and slower fluxes (baseflow from the aquifer).

The balance between these components is a delicate part of the calibration process for hydrological models. A known limitation of the SWAT model is underestimation of surface and subsurface runoff compared with percolation to the aquifer (Fu et al., 2018). However, in small watersheds with a shallow hydrological network, as simulated here, there is a substantial influence of the rapid hydrological response on discharge. The calibration of soil parameters is considered to correct this underestimation by increasing the subsurface runoff and by better representing the processes induced by the possible presence of tile drainage within the watershed, bringing the model to fit the observed discharge.

It can thus be assumed that good calibration of discharge is a substantially robust indication of good simulation of rapid fluxes such as surface and subsurface runoff. The NSE values, showing very good results for peak discharge, and the NSEsqrt and Pbias values, showing good simulation of average water volume, confirmed the good description of surface and subsurface runoff returned by the model. Specific calibration on runoff would be very complicated, considering the complexity of acquiring time series of data for those hydrological components.

The calibrated models were fed with data from a climate ensemble

dataset specifically developed for the Scandinavian region, but built only from the Swedish regional climate model RCA4 (Samuelsson et al., 2015) to dynamically downscale the climate data from several global circulation models. The RCA4 model is known to lie within the wetter part of the distribution of all European regional models from the EURO-CORDEX project, with a tendency to overestimate seasonal precipitation (Kotlarski et al., 2014). The use of only one RCM meant that epistemic uncertainty linked to this particular model was present through the entire dataset. Bias correction by the distribution-based scaling method (Yang et al., 2010) should have partly corrected this bias. The RCA4 dataset was locally evaluated in this study, regarding both monthly and daily scale. Comparison over a historical period between observed data and climate ensemble data showed that local climate conditions were fairly well represented by the ensemble for both temporal scales. However, an overestimation of very wet months was still apparent in our analysis, despite the bias correction process. In addition, comparison of daily rainfall indicated that the ensemble could not fully capture events with very high daily rainfall intensity. Difficulty in capturing daily extreme events is a known bias in high-resolution climate modeling (Prein et al., 2015), and can also be explained by the bias correction process applied to the dataset to reduce the seasonal/monthly overestimation of precipitations (Maraun, 2016). The over-expression of the last class in the frequency-intensity curve presented in Fig. 6 also tends towards a bias correction issue. It should be borne in mind that the correction process was conducted against the MESAN re-analysis product (Hägmark et al., 2000), and not against the observed data used in this study. The ability of the climate ensemble to describe the local climate was nevertheless acceptable. Comparison with existing bias values from other climate datasets used to conduct hydrological impact studies in the literature is complicated, given that such assessments are rarely conducted by environmental researchers at local scale.

The analysis of projected periods from the climate dataset highlighted several issues. An increase in monthly total precipitation was frequently associated with an increase in number of days with high rainfall (> 15 and > 30 mm). Similar findings were made by Klein Tank and Können (2003), who concluded that a significant part of the recent annual precipitation increase in northern Europe is due to very wet days. That study was based on observed data (1946–1999) and was thus not impacted by the bias of climate models in failing to depict extreme values. Bengtsson and Rana (2014) compared changes in annual total precipitation and number of days with > 20, > 30, and > 40 mm rainfall in southern Sweden over a 30-year period and found a significant increase in annual precipitation, which they associated with an increase in extreme daily rainfall events, but only during winter. In another study projecting the rainfall regime to the end of the century with a statistical downscaling method of two GCMs, Chen et al. (2015) found that a decreasing number of days with precipitation > 0.1 mm was associated with an increase in the average volume of rain per rainy day and the number of days with > 25 and > 40 mm rainfall. Those studies all show similar indications for southern Sweden, with an increase in precipitation associated with an increase in the number of high daily rainfall events. However, differences in definitions of indicators (annual rainfall/monthly rainfall; months included in seasonal definition; wet days and high daily rainfall threshold) hinder direct comparison of studies. SMHI's official definition of an extreme daily rainfall event in Sweden (40 mm/day) is purely meteorological and not particularly relevant in an agricultural context. In this study, the thresholds of > 15 and > 30 mm/day were mainly chosen based on the frequency-intensity diagram (Fig. 6), but are very similar to the thresholds used by Chen et al. (2015), who regarded 20 mm/day as a 2–4 times a year return event and 30 mm/day as a yearly return event. An increasing trend in high daily rainfall was identified in the present study despite the existing limitation of the climate ensemble in depicting those types of events, as shown by Figs. 4 and 5 and reported in the literature (Prein et al., 2015). This suggests that the increase in heavy rainfall events could potentially

be even more significant than reported here.

From the output of the SWAT model, runoff/precipitation ratio was calculated as an indicator of the amount of water flowing out of the watershed through fast routes. The increase in precipitation regime observed in this study was found to be more likely to be accompanied by an increase in runoff/precipitation ratio than an increase in soil water content. Thus the greater amount of rainfall water projected for southern Sweden will not lead to more water for crops. Quite the contrary, when precipitation (total and high daily rainfall) and runoff/rainfall ratio increased, the soil water content decreased in some cases. Similarly, Destouni and Verrot (2014) used a simple rainfall/soil moisture model to simulate moisture conditions in Sweden during the 20th century and found an increasing frequency of dry pedological events and no change in frequency of wet pedological events with overall increasing precipitation. The observations on soil water content formulated here are important in light of findings that air temperature is also projected to rise overall in southern Sweden (Eklund et al., 2015). A clear increasing trend in evapotranspirative flux was found for two of our sites (Skåne and Västergötland), most likely influenced by increasing temperature. However, this is probably not the only explanation, since Eklund et al. (2015) showed that the spring and summer temperature is expected to rise slightly more at Östergötland than Västergötland. One reason for the stability of AET at Östergötland could be that overall volume of precipitation was relatively stable at that site, but associated with an increase in heavy precipitation (> 30 mm), resulting in a stable or decreasing soil water content. The assumption can be made that, despite the rise in temperature, AET will not increase because of lack of available water in the system for evapotranspiration, including soil water. This assumption is consistent with findings in the global study conducted by Jung et al. (2010) and the regional study by Destouni and Verrot (2014).

There are uncertainties associated with any modeling work. In this study, we attempted to minimize and identify the main uncertainties linked to SWAT modeling and to the use of data from climate models. Uncertainties arising from inability of the SWAT model to precisely describe the internal fluxes of the catchment water cycle were reduced through a careful calibration process and analysis of all hydrological components of the model. In climate model projection, an ensemble of several climate models was used to reduce the uncertainty linked to individual models.

5. Conclusions

This study investigated the relationship between rainfall indicators and monthly water distribution within the hydrological systems of three agricultural watersheds in Sweden, using regionalized, bias-corrected, climate datasets to feed the agro-hydrological model SWAT. The rainfall data from the climate ensemble were first analyzed in terms of total monthly precipitation and frequency of daily rainfall, and then the effects on surface and subsurface hydrological fluxes and actual evapotranspiration were examined.

The climate model ensemble used was found to overestimate total precipitation in very wet months, but at the same time had difficulty representing extreme daily rainfall events. This could affect simulations of the impact on agricultural systems, where water management is a daily to multi-day process, rather than a monthly or seasonal process. Despite those limitations, the simulated rainfall amount during the cropping season increased at all three study sites in all months except September, when it decreased at two sites. An increase in total monthly precipitation was generally associated with an increase in high daily rainfall events, particularly events > 15 mm/day. It was also associated with an increase in runoff/rainfall ratio simulated by the SWAT model, but not in soil water content. Evapotranspirative flux was found to increase, but only at two of the three sites, indicating that more complex processes than a rise in temperature and AET explain the stable trend recorded for soil water content. In combination, the increase in runoff

due to heavy rainfall events and the increase in evapotranspiration due to temperature rise may mainly explain the lack of significant increase in soil water content, despite the increase in overall precipitation volume.

Thus, the present study showed that an increase in future precipitation in Sweden will not lead to an increase in soil water content for two main reasons: i) the increase in precipitation is likely to be associated with an increase in heavy precipitation events that tend to produce more runoff than soil infiltration; and ii) the increase in temperature will increase evapotranspiration, which will deplete soil water reserves.

The study could be used as a framework for similar investigations in other regions or countries. It demonstrates the importance of not only considering the average change in precipitation, but also the importance in agro-hydrological terms of considering local changes, including changes in precipitation frequencies.

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.

Acknowledgment

Thanks to Stefan Andersson at the Department of Soil and Environment, SLU, for soil data from the Swedish environmental monitoring and assessment program. We also want to thank Dr. Mary McAfee for valuable inputs and English corrections. This study was funded by the Swedish Board of Agriculture.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.agwat.2021.106766](https://doi.org/10.1016/j.agwat.2021.106766).

References

- Abbaspour, K.C., 2013. SWAT-CUP 2012: SWAT Calibration and Uncertainty Programs – A User Manual. EAWAG, Dübendorf.
- Abbaspour, K.C., Johnson, C.A., van Genuchten, M.T., 2004. Estimating uncertain flow and transport parameters using a sequential uncertainty fitting procedure. *Vadose Zone J.* 3, 1340–1352.
- Ahmadi, M., Moeini, A., Ahmadi, H., Motamedvaziri, B., Zehabiyani, G.R., 2019. Comparison of the performance of SWAT, IHACRES and artificial neural networks models in rainfall-runoff simulation (case study: Kan watershed, Iran). *Phys. Chem. Earth Parts A/B/C* 111, 65–77.
- Alfieri, L., Burek, P., Feyen, L., Forzieri, G., 2015. Global warming increases the frequency of river floods in Europe. *Hydrol. Earth Syst. Sci.* 19, 2247–2260.
- Arnold, J.G., Allen, P.M., Bernhardt, G., 1993. A comprehensive surface-groundwater flow model. *J. Hydrol.* 142, 47–69.
- Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment part I: model development. *J. Am. Water Resour. Assoc.* 34, 73–89.
- Arnold, J.G., Kiniry, J.R., Srinivasan, R., Williams, J.R., Haney, E.B., Neitsch, S.L., 2012a. Soil and Water Assessment Tool – Input/Output Documentation – Version 2012.
- Arnold, J.G., Moriasi, D.N., Gassman, P.W., Abbaspour, K.C., White, M.J., Srinivasan, R., Santhi, C., Harmel, R.D., van Griensven, A., Van Liew, M.W., Kannan, N., Jha, M.K., 2012b. Swat: model use, calibration, and validation. *Trans. ASABE* 55, 1491–1508.
- Ben-Gal, A., Karlberg, L., Jansson, P.E., Shani, U., 2003. Temporal robustness of linear relationships between production and transpiration. *Plant Soil* 251, 211–218.
- Bengtsson, L., Rana, A., 2014. Long-term change of daily and multi-daily precipitation in southern Sweden. *Hydrol. Process.* 28, 2897–2911.
- Berglund, K., Berglund, Ö., Gustafson Bjuréus, A., 2002. Markstrukturindex – ett sätt att bedöma jordarnas fysikaliska statur och odlingssystemets inverkan på markstrukturen. (Soil Structure Index – A Way of Assessing the Physical State of the Soil and the Impact of the Cultivation System on the Soil Structure). Swedish University of Agricultural Sciences Department of Soil Sciences Division of Agricultural Hydrotechnics (in Swedish).
- Beven, K.J., 2011. *Rainfall-Runoff Modelling: the Primer*. John Wiley & Sons.
- Chen, D., Achberger, C., Ou, T., Postgård, U., Walther, A., Liao, Y., 2015. Projecting future local precipitation and its extremes for Sweden. *Geogr. Ann. Ser. A Phys. Geogr.* 97, 25–39.
- Cheng, Q.-B., Reinhardt-Imjela, C., Chen, X., Schulte, A., Ji, X., Li, F.-L., 2016. Improvement and comparison of the rainfall-runoff methods in SWAT at the monsoonal watershed of Baocun. *East. China Hydrol. Sci. J.* 61, 1460–1476.
- Cook, J., Oreskes, N., Doran, P.T., Anderegg, W.R.L., Verheggen, B., Maibach, E.W., Carlton, J.S., Lewandowsky, S., Skuce, A.G., Green, S.A., Nuccitelli, D., Jacobs, P., Richardson, M., Winkler, B., Painting, R., Rice, K., 2016. Consensus on consensus: a synthesis of consensus estimates on human-caused global warming. *Environ. Res. Lett.* 11, 048002.
- Dastane, N.G., FAO, 1974. *Effective Rainfall in Irrigated Agriculture*. Food and Agriculture Organization of the United Nations.
- De Toro, A., Eckersten, H., Nkurunziza, L., von Rosen, D., 2015. *Effects of Extreme Weather on Yield of Major Arable Crops in Sweden*.
- Destouni, G., Verrot, L., 2014. Screening long-term variability and change of soil moisture in a changing climate. *J. Hydrol.* 516, 131–139.
- Detlef, P.V., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S., Rose, S., 2011. The representative concentration pathways: an overview. *Clim. Change* 109, 5–31.
- Douglas-Mankin, K.R., Srinivasan, R., Arnold, J.G., 2010. Soil and water assessment tool (SWAT) model: current developments and applications. *Trans. ASABE* 53, 1423–1431.
- Eckersten, H., Herrmann, A., Kornher, A., Halling, M., Sindhøj, E., Lewan, E., 2012. Predicting silage maize yield and quality in Sweden as influenced by climate change and variability. *Acta Agric. Scand. Sect. B Soil Plant Sci.* 62, 151–165.
- Eklund, A., Axén Mårtensson, J., Bergström, S., Björck, E., Dahné, J., Lindström, L., Olsson, J., Simonsson, L., Sjökvist, E., 2015. *Sveriges framtida klimat: Underlag till Dricksvattenutredningen (Swedish Future Climate: Basis for Drinking Water Study)*. SMHI (in Swedish).
- EuroSTAT, 2016. *Agri-Environmental Indicator – Irrigation*.
- Fu, C., Lee, X., Griffis, T.J., Baker, J.M., Turner, P.A., 2018. A modeling study of direct and indirect N₂O emissions from a representative catchment in the U.S. Corn Belt. *Water Resour. Res.* 54, 3632–3653.
- Gädeke, A., Pohle, I., Koch, H., Grünwald, U., 2017. Trend analysis for integrated regional climate change impact assessments in the Lusatian river catchments (north-eastern Germany). *Reg. Environ. Change* 17, 1751–1762.
- Gassman, P.W., Osei, E., Saleh, A., Hauck, L.M., 2002. Application of an environmental and economics modeling system for watershed assessments. *J. Am. Water Resour. Assoc.* 38, 423–438.
- Gassman, P.W., Reyes, M.R., Green, C.H., Arnold, J.G., 2007. The soil and water assessment tool: historical development, applications, and future research directions. *Trans. ASABE* 50, 1211–1250.
- Gassman, P.W., Sadeghi, A.M., Srinivasan, R., 2014. Applications of the SWAT model special section: overview and insights. *J. Environ. Qual.* 43, 1–8.
- Grusson, Y., Anctil, F., Sauvage, S., Sánchez Pérez, J.M., 2018. Coevolution of hydrological cycle components under climate change: the case of the Garonne river in France. *Water* 10, 1870.
- Hägglmark, L., Ivarsson, K.I., Gollvik, S., Olofsson, P.O., 2000. Mesan, an operational mesoscale analysis system. *Tellus A Dyn. Meteorol. Oceanogr.* 52, 2–20.
- Hanks, R.J., Rasmussen, V.P., 1982. Predicting crop production as related to plant water stress. In: Brady, N.C. (Ed.), *Advances in Agronomy*. Academic Press, pp. 193–215.
- Hargreaves, G.H., Samani, Z.A., 1985. Reference crop evapotranspiration from temperature. *Appl. Eng. Agric.* 1, 96–99.
- Hartmann, D.L., Klein Tank, A.M.G., Rusticucci, M., Alexander, L.V., Brönnimann, S., Charabi, Y., Dentener, F.J., Dlugokencky, E.J., Easterling, D.R., Kaplan, A., Soden, B. J., Thorne, P.W., Wild, Martin, Zhai, P.M., 2013. Observations: atmosphere and surface. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Hawkins, R.H., 2014. *Curve Number Method: Time to Think A New?* American Society of Civil Engineers.
- Hawkins, R.H., Ward, T.J., Woodward, D.E., Van Mullem, J.A., 2009. *Curve Number Hydrology: State of the Practice*. American Society of Civil Engineers.
- Held, I.M., Soden, B.J., 2006. Robust responses of the hydrological cycle to global warming. *J. Clim.* 19, 5686–5699.
- Hillel, D., Guron, Y., 1973. Relation between evapotranspiration rate and maize yield. *Water Resour. Res.* 9, 743–748.
- Jacob, D., Petersen, B.E., Egger, B., Alias, A., Christensen, O., Bouwer, L., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., Kröner, N., Kotlarski, S., Kriegsmann, A., Martin, E., van Meijgaard, E., Moseley, C., Pfeifer, S., Preuschmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M., Samuelsson, P., Somot, S., Soussana, J.-F., Teichmann, C., Valentini, R., Vautard, R., Weber, B., Yiou, P., 2014. EURO-CORDEX: new high-resolution climate change projections for European impact research. *Reg. Environ. Change* 14, 563–578.
- Jiménez Cisneros, B.E., Oki, T., Arnell, N.W., Benito, G., Cogley, J.G., Döll, P., Jiang, T., Mwakalila, S.S., 2014. Freshwater resources. In: Field, C.B., Barros, V.R., Dokken, D. J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 229–269.
- Juhola, S., Klein, N., Käyhkö, J., Schmid Neset, T.-S., 2017. Climate change transformations in Nordic agriculture? *J. Rural Stud.* 51, 28–36.
- Jung, M., Reichstein, M., Ciais, P., Seneviratne, S.I., Sheffield, J., Goulden, M.L., Bonan, G., Cescatti, A., Chen, J., de Jeu, R., Dolman, A.J., Eugster, W., Gerten, D.,

- Gianelle, D., Gobron, N., Heinke, J., Kimball, J., Law, B.E., Montagnani, L., Mu, Q., Mueller, B., Oleson, K., Papale, D., Richardson, A.D., Rouspard, O., Running, S., Tomelleri, E., Viovy, N., Weber, U., Williams, C., Wood, E., Zaehle, S., Zhang, K., 2010. Recent decline in the global land evapotranspiration trend due to limited moisture supply. *Nature* 467, 951–954.
- Kirkham, M.B., 2005. Chapter 27 – Water and yield. In: Kirkham, M.B. (Ed.), *Principles of Soil and Plant Water Relations*. Academic Press, Burlington, pp. 469–484.
- Klein Tank, A.M.G., Können, G.P., 2003. Trends in indices of daily temperature and precipitation extremes in Europe, 1946–99. *J. Clim.* 16, 3665–3680.
- Kotlarski, S., Keuler, K., Christensen, O.B., Colette, A., Déqué, M., Gobiet, A., Goergen, K., Jacob, D., Lüthi, D., van Meijgaard, E., Nikulin, G., Schär, C., Teichmann, C., Vautard, R., Warrach-Sagi, K., Wulfmeyer, V., 2014. Regional climate modeling on European scales: a joint standard evaluation of the EURO-CORDEX RCM ensemble. *Geosci. Model Dev.* 7, 1297–1333.
- Koutroulis, A.G., Papadimitriou, L.V., Grillakis, M.G., Tsanis, I.K., Wyser, K., Betts, R.A., 2018. Freshwater vulnerability under high end climate change. A pan-European assessment. *Sci. Total Environ.* 613–614, 271–286.
- Kristensen, K., Schelde, K., Olesen, J.E., 2011. Winter wheat yield response to climate variability in Denmark. *J. Agric. Sci.* 149, 33–47.
- Kvalvik, L., Dalmannsdottir, S., Dannevig, H., Hovelsrud, G., Rønning, L., Uleberg, E., 2011. Climate change vulnerability and adaptive capacity in the agricultural sector in Northern Norway. *Acta Agric. Scand. Sect. B Soil Plant Sci.* 61, 27–37.
- Lobanova, A., Liersch, S., Nunes, J.P., Didovets, I., Stagl, J., Huang, S., Koch, H., Rivas López, Md.R., Maule, C.F., Hattermann, F., Krysanova, V., 2018. Hydrological impacts of moderate and high-end climate change across European river basins. *J. Hydrol. Reg. Stud.* 18, 15–30.
- Mann, H.B., Whitney, D.R., 1947. On a test of whether one of two random variables is stochastically larger than the other. *Ann. Math. Stat.* 18, 50–60.
- Maracchi, G., Sirotenko, O., Bindi, M., 2005. Impacts of present and future climate variability on agriculture and forestry in the temperate regions: Europe. In: Salinger, J., Sivakumar, M.V.K., Motha, R.P. (Eds.), *Increasing Climate Variability and Change: Reducing the Vulnerability of Agriculture and Forestry*. Springer, Netherlands, Dordrecht, pp. 117–135.
- Maraun, D., 2016. Bias correcting climate change simulations – a critical review. *Curr. Clim. Change Rep.* 2, 211–220.
- McCabe, G.J., Wolock, D.M., 2015. Increasing northern hemisphere water deficit. *Clim. Change* 132, 237–249.
- Milly, P.C.D., Dunne, K.A., Vecchia, A.V., 2005. Global pattern of trends in streamflow and water availability in a changing climate. *Nature* 438, 347–350.
- Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE* 50, 885–900.
- Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., Wilbanks, T.J., 2010. The next generation of scenarios for climate change research and assessment. *Nature* 463, 747–756.
- Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I – a discussion of principles. *J. Hydrol.* 10, 282–290.
- Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2011. *Soil and Water Assessment Tool – Theoretical Documentation – Version 2009*.
- Olesen, J.E., 2005. Climate change and CO₂ effects on productivity of Danish agricultural systems. *J. Crop Improv.* 13, 257–274.
- Olesen, J.E., Bindi, M., 2002. Consequences of climate change for European agricultural productivity, land use and policy. *Eur. J. Agron.* 16, 239–262.
- Olesen, J.E., Trnka, M., Kersebaum, K.C., Skjelvåg, A.O., Seguin, B., Peltonen-Sainio, P., Rossi, F., Kozyra, J., Micale, F., 2011. Impacts and adaptation of European crop production systems to climate change. *Eur. J. Agron.* 34, 96–112.
- Olivera, F., Valenzuela, M., Srinivasan, R., Choi, J., Cho, H., Koka, S., Agrawal, A., 2006. ARCGIS-SWAT: a geodata model and GIS interface for SWAT. *JAWRA J. Am. Water Resour. Assoc.* 42, 295–309.
- Oudin, L., Andréassian, V., Mathevet, T., Perrin, C., Michel, C., 2006. Dynamic averaging of rainfall-runoff model simulations from complementary model parameterizations. *Water Resour. Res.* 42, 42.
- Ozturk, I., Sharif, B., Baby, S., Jabloun, M., Olesen, J.E., 2017. The long-term effect of climate change on productivity of winter wheat in Denmark: a scenario analysis using three crop models. *J. Agric. Sci.* 155, 733–750.
- Pascual, D., Pla, E., Lopez-Bustins, J.A., Retana, J., Terradas, J., 2014. Impacts of climate change on water resources in the Mediterranean Basin: a case study in Catalonia, Spain. *Hydrol. Sci. J.* 1–16.
- Patil, R.H., Lægdsmand, M., Olesen, J.E., Porter, J.R., 2010. Growth and yield response of winter wheat to soil warming and rainfall patterns. *J. Agric. Sci.* 148, 553–566.
- Peltonen-Sainio, P., Jauhiainen, L., Hakala, K., Ojanen, H., 2009. Climate change and prolongation of growing season: changes in regional potential for field crop production in Finland. *Agric. Food Sci.* 18, 171 (+).
- Peltonen-Sainio, P., Rajala, A., Känkänen, H., Hakala, K., 2015. Chapter 4 – Improving farming systems in northern Europe. In: Sadras, V.O., Calderini, D.F. (Eds.), *Crop Physiology*, Second edition. Academic Press, San Diego, pp. 65–91.
- Prein, A.F., Gobiet, A., Truhetz, H., Keuler, K., Goergen, K., Teichmann, C., Fox Maule, C., Meijgaard, E., Déqué, M., Nikulin, G., Vautard, R., Colette, A., Kjellström, E., Jacob, D., 2015. Precipitation in the EURO-CORDEX 0.11° and 0.44° simulations: high resolution, high benefits? *Clim. Dyn.* 46, 383–412.
- Pulatov, B., Linderson, M.-L., Hall, K., Jönsson, A.M., 2015. Modeling climate change impact on potato crop phenology, and risk of frost damage and heat stress in northern Europe. *Agric. For. Meteorol.* 214, 281–292.
- Putnam, A.E., Broecker, W.S., 2017. Human-induced changes in the distribution of rainfall. *Sci. Adv.* 3, e1600871.
- Qi, J., Lee, S., Zhang, X., Yang, Q., McCarty, G.W., Moglen, G.E., 2020. Effects of surface runoff and infiltration partition methods on hydrological modeling: a comparison of four schemes in two watersheds in the Northeastern US. *J. Hydrol.* 581, 124415.
- Roudier, P., Andersson, J.M., Donnelly, C., Feyen, L., Greuell, W., Ludwig, F., 2015. Projections of future floods and hydrological droughts in Europe under a +2°C global warming. *Clim. Change* 1–15.
- Sahu, R.K., Mishra, S.K., Eldho, T.I., 2012. Performance evaluation of modified versions of SCS curve number method for two watersheds of Maharashtra, India. *ISH J. Hydraul. Eng.* 18, 27–36.
- Samuelsson, P., Gollvik, S., Kupiainen, M., Kourzeneva, E., van de Berg, W.J., 2015. The Surface Processes of the Rossby Centre Regional Atmospheric Climate Model (RCA4). SMHI.
- SCS, 1986. *Urban hydrology for small watersheds*. Engineering Division Technical Release, p. 55.
- Seiller, G., Antcil, F., Perrin, C., 2012. Multimodel evaluation of twenty lumped hydrological models under contrasted climate conditions. *Hydrol. Earth Syst. Sci.* 16, 1171–1189.
- Seiller, G., Roy, R., Antcil, F., 2017. Influence of three common calibration metrics on the diagnosis of climate change impacts on water resources. *J. Hydrol.* 547, 280–295.
- Shani, U., Ben-Gal, A., Tripler, E., Dudley Lynn, M., 2007. Plant response to the soil environment: an analytical model integrating yield, water, soil type, and salinity. *Water Resour. Res.* 43, 43.
- Stagge, J., Tallaksen, L., Rizzi, J., 2015. Future meteorological drought: projections of regional climate models for Europe. *EGU General Assembly Conference Abstracts*, p. 7749.
- Strandberg, G., Barring, L., Hansson, U., Jansson, C., Jones, C., Kjellström, E., Kupiainen, M., Nikulin, G., Samuelsson, P., Ullerstig, A., 2015. CORDEX Scenarios for Europe from the Rossby Centre Regional Climate Model RCA4, RMK, Rapport Meteorologi och Klimatologi. SMHI, p.75.
- Uleberg, E., Hanssen-Bauer, I., van Oort, B., Dalmannsdottir, S., 2014. Impact of climate change on agriculture in Northern Norway and potential strategies for adaptation. *Clim. Change* 122, 27–39.
- Vautard, R., Gobiet, A., Jacob, D., Belda, M., Colette, A., Déqué, M., Fernández, J., García-Díez, M., Goergen, K., Güttler, I., Halenka, T., Karacostas, T., Katragkou, E., Keuler, K., Kotlarski, S., Mayer, S., van Meijgaard, E., Nikulin, G., Patarčić, M., Scinocca, J., Sobolowski, S., Suklitsch, M., Teichmann, C., Warrach-Sagi, K., Wulfmeyer, V., Yiou, P., 2013. The simulation of European heat waves from an ensemble of regional climate models within the EURO-CORDEX project. *Clim. Dyn.* 41, 2555–2575.
- Verrot, L., Destouni, G., 2016. Worldwide soil moisture changes driven by future hydro-climatic change scenarios. *Hydrology and Earth System Sciences Discussions*.
- Wiklert, P., Andersson, S., Weidow, B., 1983. *Studier av markprofiler i svenska åkerjordar: En faktsammansättning*. Swedish University of Agricultural Sciences (in Swedish).
- Williams, J.R., 1995. The EPIC model. In: Singh, V.P. (Ed.), *Computer Models of Watershed Hydrology*. Chapter 25.
- Wiréhn, L., 2018. Nordic agriculture under climate change: a systematic review of challenges, opportunities and adaptation strategies for crop production. *Land Use Policy* 77, 63–74.
- Yang, J., Reichert, P., Abbaspour, K.C., Xia, J., Yang, H., 2008. Comparing uncertainty analysis techniques for a SWAT application to the Chaohe Basin in China. *J. Hydrol.* 358, 1–23.
- Yang, W., Andréasson, J., Phil Graham, L., Olsson, J., Rosberg, J., Wetterhall, F., 2010. Distribution-based scaling to improve usability of regional climate model projections for hydrological climate change impacts studies. *Hydrol. Res.* 41, 211–229.
- Yen, H., White, M.J., Jeong, J., Arabi, M., Arnold, J.G., 2015. Evaluation of alternative surface runoff accounting procedures using SWAT model. *Int. J. Agric. Biol. Eng.* 8, 54–68.
- Zhang, D., Lin, Q., Chen, X., Chai, T., 2019. Improved curve number estimation in SWAT by reflecting the effect of rainfall intensity on runoff generation. *Water* 11, 163.
- Zhang, Y., Su, F., Hao, Z., Xu, C., Yu, Z., Wang, L., Tong, K., 2015. Impact of projected climate change on the hydrology in the headwaters of the Yellow River basin. *Hydrol. Process.* 29, 4379–4397.