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# Climate change intensifies hydrological seasonality in Denmark: Insights from an integrated model assessment

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**Abstract.** Temperate regions across Europe, such as Denmark, are projected to be subjected to substantial changes in the hydrological cycle due to climate change. Changes in climate can materialize as general changes in long term means, extremes, or in seasonal patterns, e.g., dampening or intensification of the seasonal contrasts. Changes in seasonal patterns can affect the hydrological cycle in various ways, due to the interlinkage between hydrological compartments. To detect, track and quantify the impact of changes in climate and seasonal patterns, integrated hydrological modelling is needed. This makes Denmark an ideal test case due to the established integrated and physically based National Hydrological Model of Denmark (DK-model). Utilizing climate projections from 17 RCP8.5 climate models, downscaled and bias-corrected for Denmark, we calculate climate change impacts on both overall values and seasonality for the variables soil moisture, streamflow, shallow and deeper groundwater to the end of the century. Moreover, standardized hydrological drought indices are calculated for the same variables. Climate change projections point towards a future with higher annual precipitation, mainly due to wetter winters, while climatic water balance deficits increase during summer; thus, intensifying the seasonal contrast. The increased contrast is reappearing in the fast-responding hydrological variable, soil moisture; while streamflow and shallow groundwater clearly reproduce increase during the wetter winter, the summer signal differs. The deep groundwater systems experience higher future groundwater heads across the entire year. Common for all variables is a larger seasonality, defined as contrast between intra-annual low and highs. Notably, the ensemble of hydrological projections is more in agreement regarding the seasonal contrast than on the direction of absolute change, with results agreeing for 85 % to 99 % of the area of Denmark on increased seasonality, whereas only agreeing for 50 % to 98 % on the absolute direction of that change. The drought indices exhibit a similar seasonal change, with more droughts during summer and more wet anomalies during winter for soil moisture, while summer droughts for streamflow and shallow groundwater partially are buffered by wetter winters and the related recharge increase. In summary, the results indicate that despite considerable increases in precipitation, projected climate change for Denmark is expected to enhance hydrological seasonality instead of producing a uniform transition to a wetter regime, potentially impacting the climate adaptation and mitigation effort, agricultural yields, and water supply.

## 1 Introduction

Climate change impacts on hydrology are a persistent and imminent global concern. Temperate regions, such as Northern Europe, are projected to experience increases in mean temperatures and precipitation (Bednar-Friedl et al., 2022). These changes affect the entire hydrological cycle (Douville et al., 2023) and have been shown in numerous studies to cause an overall increase in stream discharge (Lobanova et al., 2018). The impacts on the hydrological cycle are, however, highly interlinked, and responses in different compartments of the hydrological system have the potential to either buffer or amplify climate change impacts (Şen, 2021). Changes in the seasonal distribution of hydroclimatic variables are known from studies around the world (Caretta et al., 2022; Konapala et al., 2020; Nile et al., 2025). Such changes could be acceleration of the existing seasonality pattern (Eisner et al., 2017; Kay, 2021; Sanderson et al., 2012), shifts in spring flood timing (Ford et al., 2020), or seasonal shifts in peak irrigation water demands (Wada et al., 2013) and have the potential to impact numerous ecosystem services, including water availability, hydropower production (Golgojan et al., 2024), and ecology. Depending on their timing and magnitude, such changes may have either positive or negative effects on anthropogenic systems (Ruosteenoja et al., 2020). For example, higher temperatures may lengthen the growing and harvesting season in Northern Europe (Wiréhn, 2018), but they may also increase drought risk (Tootoonchi et al., 2025). Likewise, recharge rates during winter may increase while at the same time, the recharge season may shorten (Hughes et al., 2021), and increased precipitation may elevate flood risk, while simultaneously enhancing groundwater resources available for summer irrigation. Consequently, assessments of climate change impacts on the hydrological system should be conducted in an integrated framework that captures multiple components of the natural system (Dahal et al., 2025; Mourot et al., 2025), including soils, vegetation, surface water, and groundwater. Such assessments require (i) modelling systems capable of simulating the entire hydrological cycle and (ii) analytical frameworks that enable consistent comparison of changes and anomalies across variables and hydrological compartments.

In this context, Denmark represents an ideal study area, as it allows for the use of the well-established National Hydrological Model, the DK-model (Højberg et al., 2013; Stisen et al., 2019), a physically-based integrated distributed hydrological model covering the entire hydrological cycle. Denmark is characterized by a high degree of connectivity between surface water and groundwater (Sechu et al., 2022), and the DK-model has been developed and adapted to reproduce this co-dependency. The Danish case is also favoured by availability of an abundance of high-quality data.

Climate change impact studies of the hydrological cycle in Denmark were first conducted in the late 2000s. The first national dataset of bias-corrected climate model data based on IPCC AR4 (Intergovernmental Panel on Climate Change (IPCC), 2007) was generated (van Roosmalen et al., 2010) and assessed using local hydrological models (e.g., van Roosmalen et al., 2007, 2009), and was later expanded with additional emission scenarios and downscaling methods (Seaby et al., 2013). This updated dataset was subsequently used to drive the then-current version of the DK-model, supplying data to the earliest national climate adaptation platforms, such as www.klimatilpasning.dk, as well as feeding into numerous local climate change studies (e.g., Karlsson et al., 2016; Kidmose et al., 2013; Randall et al., 2013; Sonnenborg et al., 2015). In 2019, the national climate data set was updated to IPCC AR5 (Intergovernmental Panel on Climate Change (IPCC), 2013) by Pasten-Zapata et al. (2019), and run through a new version of the DK-model by Henriksen et al. (2020), making national climate change impacts available via the Hydrologic Information and Prognosis System (HIP), www.hipdata.dk (Henriksen et al., 2022a). Three studies have since been published on the national hydrological climate assessment, describing the climate change sensitivity of the groundwater system (Seidenfaden et al., 2022), climate impact on ecological flow and shallow groundwater for two subcatchments in the context of water resource assessments (Henriksen et al., 2021), and the downscaling of 500 m climate change outputs of groundwater table depth to 100 m resolution using machine learning (Schneider et al., 2022c). The present study utilises the same climate runs, but in contrast to the previous studies, it focuses on exploring the increased seasonality under future climate and increased variability by including hydrological drought indices in the analysis.

Within drought and hydroclimate research, standardized drought indices are routinely used for describing dry extremes for model and observational time series. These indices are well-suited for investigating changes across multiple hydrological variables, as they are standardized to common scales, and therefore facilitate direct comparison across compartments. The indices represent deviations from statistically "normal" conditions, and they can therefore also be used to describe wet extremes. The DK-model, combined with the indices framework, is therefore a powerful tool for investigating the propagation of climate change signals through the entire hydrological cycle, including changes in the seasonality (Schneider et al., 2025).

Despite the extensive literature on climate change impacts on hydrology, many assessments focus on changes in long-term means or extreme events (floods and droughts), while changes in the seasonal patterns in the hydrological system receive less attention (Caretta et al., 2022). Yet, climate projections increasingly suggest that changes in seasonality (Arora et al., 2025; Konapala et al., 2020) – rather than uniform changes in mean conditions – may dominate future hydrological impacts. Moreover, the majority of studies that include assessments of impacts on seasonality focus on single compartments, e.g., groundwater (Hughes et al., 2021), soil moisture (Boeing et al., 2025), or more commonly streamflow (Dallison et al., 2022; Eisner et al., 2017; Kay, 2021; Murray et al., 2023; Rottler et al., 2021; Sanderson et al., 2012). Others have used separate hydrological models for analysing impacts on streamflow and groundwater (Hannaford et al., 2023) or connecting changes in meteorological variables to impacts on a single hydrological variable (Meresa et al., 2023). We see a lack of studies assessing climate change impacts on seasonality in an integrated manner across the entire hydrological system. Seasonality in our context is understood as the amplitude between intra-annual low/dry and high/wet conditions.

The paper will investigate the following research questions:

- How does the projected increase in climatic seasonality propagate through the different compartments of the hydrological system?
- To what extent does climate change modify hydrological anomalies, as captured by hydrological indices, beyond changes in mean conditions?

## 2 Study area: Denmark

The modelling domain covers the land phase of Denmark with a total area of around 43,000 km$^2$ (excluding a few smaller islands). Topography is generally flat, with the highest elevation of 170 m.a.s.l. The shallow geology of Denmark is largely formed by the late glaciations, particularly the advance of the ice sheet during the Weichselian glaciation, marked by the main stationary line splitting the peninsula of Jutland into a North-Eastern and South-Western part. North and East of the main stationary line, the landscape and surface geology of Eastern Jutland and the major islands of Funen and Zealand are dominated by moraine deposits. The outwash plain in the South and Western parts of Jutland is dominated by coarser grained sediments of sand and gravel with hill islands from previous glaciations. The deeper pre-quaternary geology consists of large sedimentary basins of sand and clay underlaid by carbonate rocks forming several chalk aquifers (Schack Pedersen et al., 2018). The depth to the chalk varies greatly, from shallow in Zealand and Northern Jutland to deep in the southern and western parts of the country.

The climate in Denmark is characterized as humid and temperate with average annual precipitation of 860 mm/y ranging from 700 mm/y in Zealand to 1100 mm/y in Western Jutland. Annual temperatures are 8-9 °C and reference evapotranspiration is around 560 mm/y (Klimanormaler for Danmark, 2025). The hydroclimate is energy-limited with high water availability during the winter season, where groundwater recharge, groundwater levels, and stream discharges are high. During summer, the balance between precipitation and evapotranspiration is reversed, with evapotranspiration exceeding precipitation.

The current hydroclimatic variability is illustrated in Fig. 1 for the climate normal period 1991-2020, expressed as average monthly values for precipitation, actual evapotranspiration, runoff, groundwater recharge in mm, and average states for root zone soil moisture and depth to the phreatic surface. Precipitation in Fig. 1 is observed, while the remaining fluxes and states are simulated using the DK-model (see Sect. 3). The winter surplus in precipitation relative to actual evapotranspiration largely dictates the hydrological seasonality by generating groundwater recharge and runoff. During the summer period, where actual evapotranspiration exceeds precipitation (Fig. 1a), the runoff is sustained by groundwater and maintains relatively high runoff rates despite low recharge rates (Fig. 1b). The distinct seasonality is also visible in root zone soil moisture and shallow groundwater level (depth to phreatic surface) fluctuations, which reach the annual low around July to August for soil moisture and about one to two months later for shallow groundwater (Fig. 1c). This coincides with the time of year when the precipitation again exceeds actual evapotranspiration.

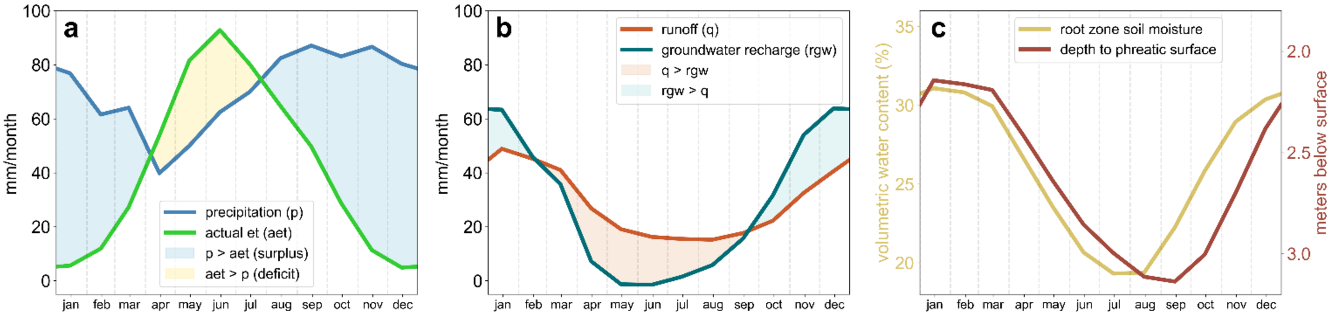

**Figure 1:** Average hydro-climatic variables for Denmark based on the climate normal 1990-2020. Fluxes for precipitation and actual evapotranspiration (a) and for runoff and groundwater recharge (b) are in mm/month while the average states for root zone soil moisture and depth to the phreatic surface (c) are in volumetric water content and meters below surface respectively.

The land use in Denmark is dominated by agriculture, which occupies around 60 % of the area, while the remaining is primarily urban and forest. Groundwater abstraction accounts for 10 mm to 25 mm per year at the national scale, on average, half of this is for irrigation, the rest primarily for public water supply (Thorling et al., 2024). These abstraction amounts account for roughly 3 % to7 % of the net precipitation; however, abstractions vary spatially. Irrigation occurs mainly on the sandy soils in Western Jutland while public water supply is distributed across the country, with the largest production around the larger cities.

## 3 Data and Methods

### 3.1 DK-model

The National Hydrological Model of Denmark (DK-Model) is a distributed and integrated hydrological model coupling surface and groundwater processes while representing the major anthropogenic impacts on the hydrological system (Henriksen et al., 2003, 2020; Højberg et al., 2013; Stisen et al., 2019). The model development has been ongoing since it was initiated in 1996 and has been guided by a combination of research, technical developments, and user requirements. The model is applied for a series of water management tasks at the national scale, such as water resources assessments (Henriksen et al., 2024), climate change impacts (Seidenfaden et al., 2022), nitrate transport (Andersen et al., 2025), and monitoring and forecasting systems (Henriksen et al., 2018; Liu et al., 2026).

#### 3.1.1 Model setup

The model setup is based on the MIKE SHE code (Abbott et al., 1986; DHI, 2024). It couples a 3D finite difference representation of groundwater flow with a 2D description of overland flow, a 1D representation of root zone processes, and a simple routing of streamflow. The version employed in the current study is in a 500 m grid resolution with transient simulation at maximum timesteps of 24 hours.

Climate forcing data are provided by the Danish Meteorological Institute (Scharling, 1999a, b), and measured precipitation is bias corrected for wind-induced undercatch (Stisen et al., 2012). The soil parametrization is based on a digital map of Danish soil types (Børgesen et al., 2009), with associated soil physical parameters. Artificial drainage, which is common throughout Denmark (Olesen, 2009), is conceptualized by drain depth and resistances (time constant) distributed according to topographical variability, landcover and soil types with associated soil physical parameters (Schneider et al., 2022b). The hydrostratigraphy is described as layers of varying thickness based on the hydrogeological model of Denmark (Arvidsen et al., 2020), with approximately ten computational layers. 30,000 km of stream network is represented explicitly in the model by location, connections, and stream profiles.

An important part of the model setup is the anthropogenic impacts of groundwater abstraction, irrigation, and point-discharges to streams. Groundwater pumping is included based on extensive databases of wells and abstractions from Jupiter, the National Well Database (GEUS, 2025), with more than 10,000 wells included, while irrigation is calculated based on crop water demand deficits, where around 19,000 irrigation wells are represented.

### 3.1.2 Model calibration and performance

Being a national-scale integrated model, the DK-Model is computationally demanding to run and calibrate. The complexity is further increased by the fact that the integrated nature and multiple applications require model optimization and evaluation across a range of metrics. For the version used in this study, the calibration of the DK-model utilized observational datasets for stream discharge, groundwater levels and irrigation to form a range of performance targets that are combined in one final objective function.

Stream discharge was evaluated based on the Kling-Gupta efficiency (KGE) (Gupta et al., 2009), as well as annual and summer water balances calculated for 305 daily discharge stations. Groundwater levels are evaluated based on three groups of data: (i) the general groundwater heads in the saturated zone as observed in roughly 39,500 wells with at least one observation; (ii) the annual groundwater table amplitude as observed in 400 wells with detailed timeseries; and (iii) lastly from the water stage from 19,000 small lakes identified as groundwater-fed and not coupled to the surface water system. The small lakes were regarded as observation points with a groundwater table at the surface of the digital elevation model. For groundwater level observations, an objective function based on the Continuous Ranked Probability Score (CRPS) was applied, which reduces sensitivity to single outliers in the large observation datasets (Schneider et al., 2022a). In addition, the groundwater observations were split into a shallow and a deep group (based on well filter depths below or above 10 m) to enable the separate evaluation of the model performance on shallow and deep groundwater. Annual irrigation sums for the irrigated areas, as reported in the national database Jupiter, were a target for evaluating the simulated irrigation.

The model is calibrated for the period 2000 to 2010 with a 10-year spin-up from 1990 to 1999. 44 model parameters were selected for optimization based on past experiences and sensitivity tests, while additional parameters are tied to these free parameters. The optimized parameters are mainly hydraulic conductivities in the subsurface associated with different hydrostratigraphic units, drainage parameters, and parameters associated with soil and vegetation. The Levenberg-Marquardt optimization scheme within the PEST tool (Doherty, 2002) was used as a gradient based search algorithm to minimize the combined objective function.

The model performance is summarized in Fig. 2, which displays the cumulative distributions of simulation performance for KGE, annual and summer water balance error, shallow and deep groundwater heads, and shallow and deep annual groundwater level amplitudes. Simulated streamflow (Fig. 2a) is generally in good agreement with observations, with 50 % of stations having a KGE above 0.70. Water balance errors (Fig. 2b) are balanced across the country with a low mean error (ME) and a mean absolute error (MAE) of 14 % annually and 24 % for summer months. Groundwater levels are simulated with a MAE of 2.79 m and 4.17 m for shallow and deep wells, respectively (Fig. 2c). Annual amplitudes in groundwater level fluctuations are underestimated by approximately 0.5 m for both shallow and deep wells (Fig. 2d). For further information on the DK-model calibration and performance, the reader is referred to Henriksen et al. (2020).

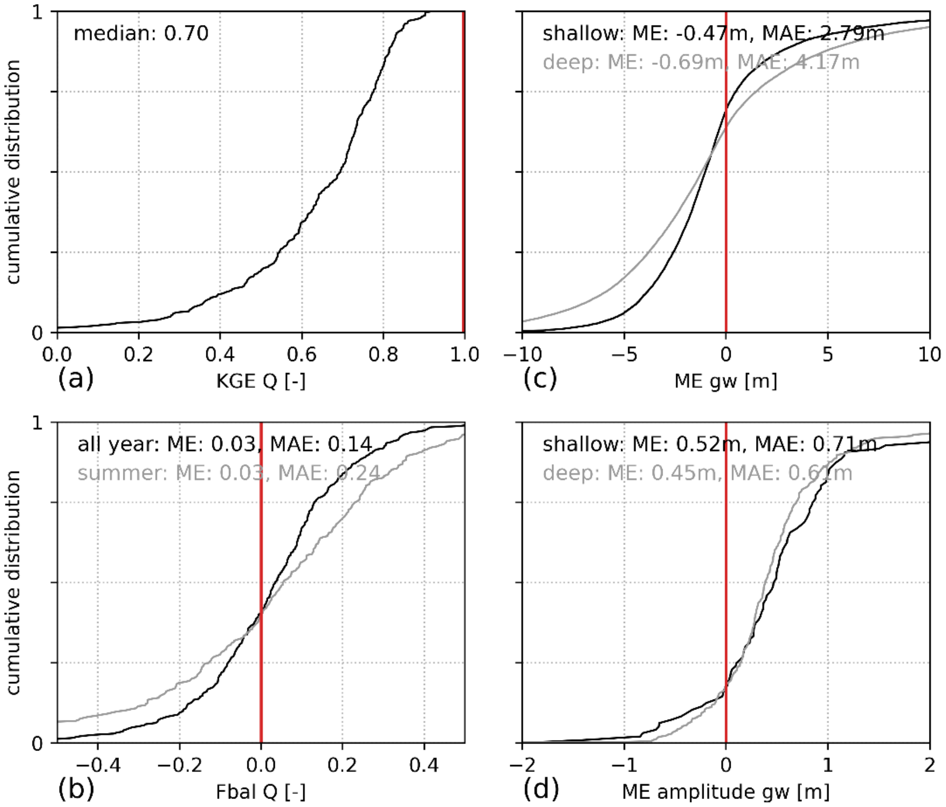

**Figure 2: DK-model calibration performance. (a): KGE [-] and (b): water balance error for 305 streamflow stations. (c): Residuals against groundwater level measurements in 11,822 shallow and 27,692 deep wells. (d): Residuals against seasonal groundwater level amplitudes in 97 shallow and 304 deep wells. Optimal values marked with red.**

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### 3.2 Climate change projections

In this study, 17 climate model projections are used to investigate the future hydrological cycle. The climate models are all part of the Euro-CORDEX project (Jacob et al., 2014), and are based on scenarios from AR5 IPCC (Intergovernmental Panel on Climate Change (IPCC), 2013). The projections are all under the RCP8.5 concentration pathways representing a business-as-usual storyline. Newer AR6 (Lee et al., 2021) climate model data are still being generated and can therefore not be utilized in the study. However, the newer SSP5-8.5 is the development scenario that comes closest to the RCP8.5. The climate models have previously been downscaled/bias-corrected to Denmark by Pasten-Zapata et al. (2019). Precipitation and temperature are downscaled by Distribution-Based Scaling (DBS) (Piani et al., 2010) using a double gamma function with a cut-off at the 90th percentile for the former and a normal distribution for the latter. The DBS is done on each grid in the gridded observational dataset (Scharling and Kern-Hansen, 2012), thus on 10 km resolution for precipitation and 20 km resolution for temperature. Potential evapotranspiration (PET) is calculated from the temperature using the Oudin formula (Oudin et al., 2005), and subsequently bias-corrected to the national gridded observation dataset (Scharling, 2001) that is based on Makkink (Makkink, 1957).

### 3.2.1 Overall future meteorological signal

The most important drivers of the hydrological cycle are precipitation and evapotranspiration. Fig. 3 displays climatologies of daily climatic water balance (precipitation – PET), as a median across the climate models, where we compare the reference period with the end-century period. In the end-century period, the dry season (characterized by negative climatic water balance) starts at the same time as in the reference period, around the beginning of April. However, it finishes later by about 20 days, around the beginning of September instead of the middle of August. Also, the deficit increases with the largest differences during July and August. In contrast, the positive climatic water balance during the recharge season (winter) increases, causing an intensification of the seasonality. The impact of this increase in seasonal contrasts in the climate model input data on the hydrological cycle is the focus of this study. See Fig. A1 for a more detailed version, including a comparison to historic observed values.

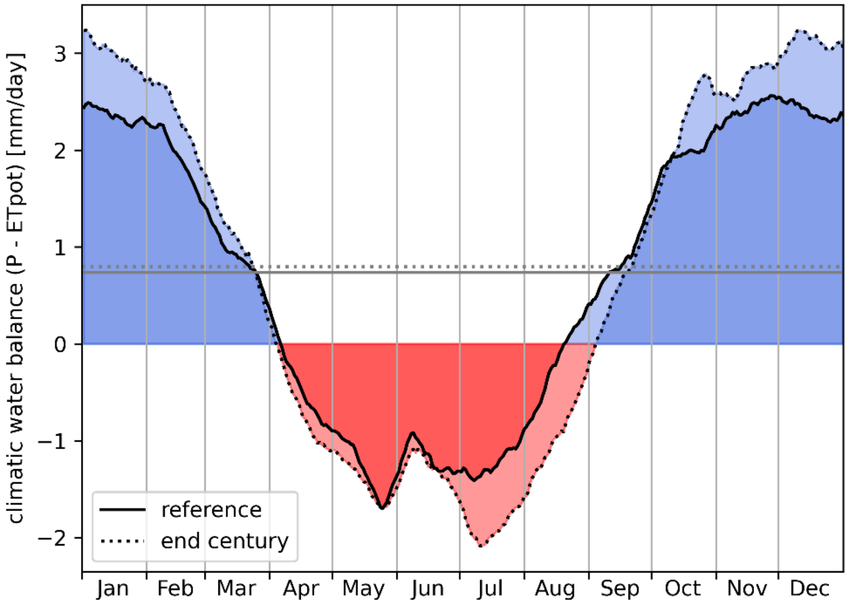

**Figure 3: Climatic water balance (precipitation – PET). Mean across Denmark of the median of the 17 climate models. Based on values for each day of the year for the reference (1991-2020) and end-century (2071-2100) period, with a 15-day moving average. The resulting yearly average values are shown as grey horizontal lines and equate to 270 mm/y in the reference period and 291 mm/y in the end-century period.**

### 3.2.2 Sea level rise

The sea level is projected to increase in the future for the Danish area (Colgan et al., 2022), even in areas counteracted by glacio-isostatic land rebound after the last glaciation (Colgan et al., 2017). In the DK-model, the current sea level is fixed at 0 m.a.sl. For future sea level projections, estimates of sea level rise are implemented using interpolations from projections by the Danish Meteorological Institute (Thejll et al., 2021), and kept constant over the period investigated (more information can be found in Henriksen et al. (2020), Sect. 2.2.1). On national scale, the end-century sea level elevation is 0.51 m.a.sl., ranging from 0.44 m.a.sl. in the northeast, where glacio-isostatic adjustments are largest, to 0.59 m.a.sl. in the south. These projections are smaller for the mid-century period, with 0.24 m.a.sl. on average, ranging from 0.19 to 0.29 m.a.sl.

### 3.2.3 Anthropogenic influence in the DK-model

The future human use of water resources is uncertain. Therefore, the annual abstraction of groundwater for water use are held constant throughout the entire future period. The constant abstraction is fixed at the average use in the years 2010 to 2019. Similarly, the wastewater outflow to the river system is fixed as the average from the period of 2001 to 2011. Also, land use is kept constant at the historical distribution. Irrigation amounts in agriculture, however, are derived from a dynamic demand-driven module, using a soil moisture threshold together with information on the location of irrigation wells as well as irrigation permits, crop type, and season. The future runs follow the same approach. Thus, irrigation can be higher or lower in the future, corresponding to an increase or decrease in the need to hold the soil moisture above the threshold. However, the irrigation amounts are still restricted by pumping limits and wells running dry, maintained at historical restrictions. In this fashion, we allow for more irrigation by farmers in response to drought, but not altering the infrastructure and regulations in place currently.

### 3.2.4 Climate change impact on soil moisture, streamflow, and groundwater levels

Climate model data is available from 1971 to the end of the 21st century. In our case, we investigate two periods: the mid-century (2041-2070) and the end-century period (2071-2100), which are compared to the historical period of the climate models called the reference period (1991-2020). Thus, changes in hydrological variables from past to future are always calculated using differences in climate model runs between future and reference period to eliminate problematic biases in the climate models.

We then focus on four compartments of the hydrological cycle: Soil moisture of the root zone, streamflow, depth to phreatic (the uppermost groundwater table), as well as the aquifer groundwater head (the deeper groundwater).

Soil moisture is extracted for each grid cell from the lumped root zone layer of the 2-layer UZ description of MIKE SHE. Thus, the depth over which soil moisture values integrate will vary depending on vegetation type and season. Soil moisture is given in volume fraction as a percentage between 0 % and 100 % (effectively limited to values between local residual and saturation water content), describing the part of the root zone volume that is water-filled. The soil moisture change is therefore reported in percentages, meaning that the changes indicate if the soil moisture is closer (positive) or further (negative) from saturation. For the indices, the former values are used for calculation.

Streamflow is simulated at every calculation point (Q-point) along the rivers, roughly every 500 meters, and given in $m^3/s$ for every 24 hours. In this paper, changes to streamflow are mainly reported as climate factors, given as $\text{streamflow}_{\text{ref}}/\text{streamflow}_{\text{future}}$, thus a value above one indicates increasing streamflow in the future, while a value below one indicates a decrease.

Groundwater is split into two distinct variables: First, the depth to the phreatic table, as a representation of the uppermost shallow groundwater, with relevance for ecosystems, river-subsurface exchange, but also affecting agriculture and infrastructure, in particular when close to the surface. Second, the aquifer groundwater head, representing the deeper groundwater, with relevance for water supply. Both variables are again extracted at every grid cell of the DK-model. The depth to the phreatic table is the depth in meters below surface. The aquifer groundwater head is calculated based on the mean simulated saturated zone head elevations across the two computational layers of the DK-model from which the largest water supply extractions occur. This means that the information on aquifer groundwater head spans different groundwater aquifers with different hydrogeological properties that are scattered across depths and area, , which can also be seen in their diverse responses to historical meteorological anomalies (Schneider et al., 2025).

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### 3.3 Hydrological indices

Standardized drought indices are routinely used for describing dry extremes in the hydrological system. If the statistics are based on an intra-annual approach for the historical period and applied for future projections, their changes also reveal information on timing and shifts of means. The hydrological indices were originally calculated for Denmark for historical periods by Henriksen et al. (2022b), based on experience from catchment studies (e.g., Karlsson et al., 2014) for soil moisture, streamflow, and both shallow and deep groundwater. Subsequently, extensive work was done to evaluate the DK-model's ability to reproduce observed signals and trends of the hydrological indices (Schneider et al., 2025), future predictions using indices have previously only been done for single catchments (Chan et al., 2021; Karlsson et al., 2015).

To investigate the changes in the hydrological system, in particular changes to the occurrences of anomalies, we calculate drought indices for multiple variables. Soil moisture is evaluated using the Empirical Standardized Soil Moisture Index (*ESSMI*) (Carrão et al., 2016). For streamflow, we used the Streamflow Drought Index (*SDI*) (Nalbantis and Tsakiris, 2009). For groundwater, we used the Standardized Groundwater Drought Index (*SGDI*) (Bhuiyan et al., 2006; Bloomfield and Marchant, 2013), where we separated the groundwater into the uppermost groundwater table (depth to phreatic) with $SGDI_{shallow}$ and the deeper aquifer groundwater head, represented by the average across the two aquifer layers with highest groundwater abstractions, referred to as $SGDI_{deep}$.

The reader is referred to Seidenfaden et al. (2025) and Schneider et al. (2025) for detailed calculation steps. Common for the chosen indices is that they represent the deviation from statistical normal conditions for a given time of year, standardized to index values. Thus, the statistical information is used to generate standardization transferrable in space, time as well as across variables, where e.g. an index value of -2 indicates that the variable is more than two standard deviations below the mean, corresponding to a severe drought category. The related categories to index values for the hydrological indices can be seen in Table 1.

The indices are all standardised indices originating from drought literature, but as they, in their formulation, describe different types of deviations from normal conditions based on standard deviation, they can also be utilised in describing wet anomalies in addition to dry anomalies. In this context, they are therefore nomenclatured as hydrological indices. The hydrological indices are supplemented by two meteorological indices, the Standardized Precipitation Index (*SPI*) (McKee et al., 1993) and the Standardized Precipitation Evapotranspiration Index (*SPEI*) (Vicente-Serrano et al., 2010).

**Table 1: Drought and wet anomaly categories based on standardized index intervals. *The category Beyond Extremes is used here as future projections of the indices may move substantially outside the "normal" given range of the indices.**

| Category | Index interval |
|---|---|
| Beyond Extreme* | >3 |
| Extremely wet | 2 to 3 |
| Severely wet | 1.5 to 2 |
| Moderately wet | 1 to 1.5 |
| Mildly wet | 0 to 1 |
| Mildly dry | -1 to 0 |
| Moderate drought | -1 to -1.5 |
| Severe drought | -1.5 to -2 |
| Extreme drought | -2 to -3 |
| Beyond Extreme* | <-3 |

The indices her are calculated for climate projections, where the thresholds for the indices are based on the statistical information from the reference period. Meaning that for each climate model, the standardization is based on the climate model data for the 1991 to 2020 reference period, and this standardization is maintained for the mid- and end-century periods. This approach makes it possible to somewhat account for climate model bias, while allowing the future indices to move beyond the standardisation constraints.

### 3.3.1 Drought severity

A commonly used drought characteristic is drought severity, defined as the accumulated index deficit under a given drought threshold (Hisdal et al., 2023). Severity, therefore, encapsulates both the duration under the threshold and the distance to the threshold. For standardized indices, this accumulated value is not directly relatable to a missing deficit water volume but is a representation of the accumulated deviation from "normal" conditions. In this study, severity is calculated for periods under –1 for droughts (dry severity) and +1 for wet conditions (wet severity).

## 4 Results

### 4.1 Overall future hydrological signal

Figure 4 displays the climate change impacts on the four major compartments of the hydrological cycle as simulated by the DK-model across the 17 climate models. Changes are presented as end-century – reference values for soil moisture [vol. %], depth to phreatic [m], and aquifer groundwater head [m]. For streamflow, changes are presented as a climate factor, i.e., end-century / reference values (see Fig. B 1 for mid-century values). All values are mean values across Denmark and presented separately for each month. The black vertical lines represent the median of these changes across all climate models, whereas the histograms summarize the climate model and temporal variability, i.e., each representing 17*30 values (climate models * years). The climatic water balance deficit during summer (compare Fig. 3) leads to a negative climate change impact on soil moisture from April to November, with the highest impact of -1.8 vol. % in August. During the winter months, soil moisture is also increasing in accordance with increased (net) precipitation amounts, where January experiences largest increases with +0.6 vol. %. Streamflow values increase across the entire year with a strong seasonal signal, ranging from a factor of 1.33 in January to a factor of 1.03 in October. This reflects the fact that the majority of Danish streams are groundwater-fed and the generally large interaction between surface water and groundwater in Denmark (Sechu et al., 2022). The stronger seasonal signal for streamflow, with almost no change during late summer and early autumn, is considered a counterbalanced effect of both increased winter precipitation and increased climatic water balance deficit during summer. Due to generally increased precipitation, in particular increased net precipitation during winter, the groundwater levels generally rise. For the depth to phreatic, climate change impacts show a clear seasonal signal, with highest increases during late winter (up to +0.27 m), and lowest rises during September and October (+0.09 m). Aquifer groundwater heads rise by slightly higher amounts, but with a much-subdued seasonal signal between +0.33 m and +0.25 m. Hence, an increased dampening of the seasonal signal in climatic water balance change can be seen when moving through the hydrological cycle from soil moisture to streamflow, to shallow groundwater, and lastly the aquifer groundwater head. This correlates with response times – from faster reacting to slower reacting – of the compartments to precipitation or precipitation anomalies (Schneider et al., 2025).

As Fig. 4 displays average values across Denmark, obviously, those values span over considerable local variations. Figure 5 shows maps of historic mean values together with the expected median climate change impact for the four hydrological variables. Values here are averages across the entire year; the appendix shows values separately for winter (DJF) and summer (JJA) seasons (Fig. B 3 and Fig. B 4).

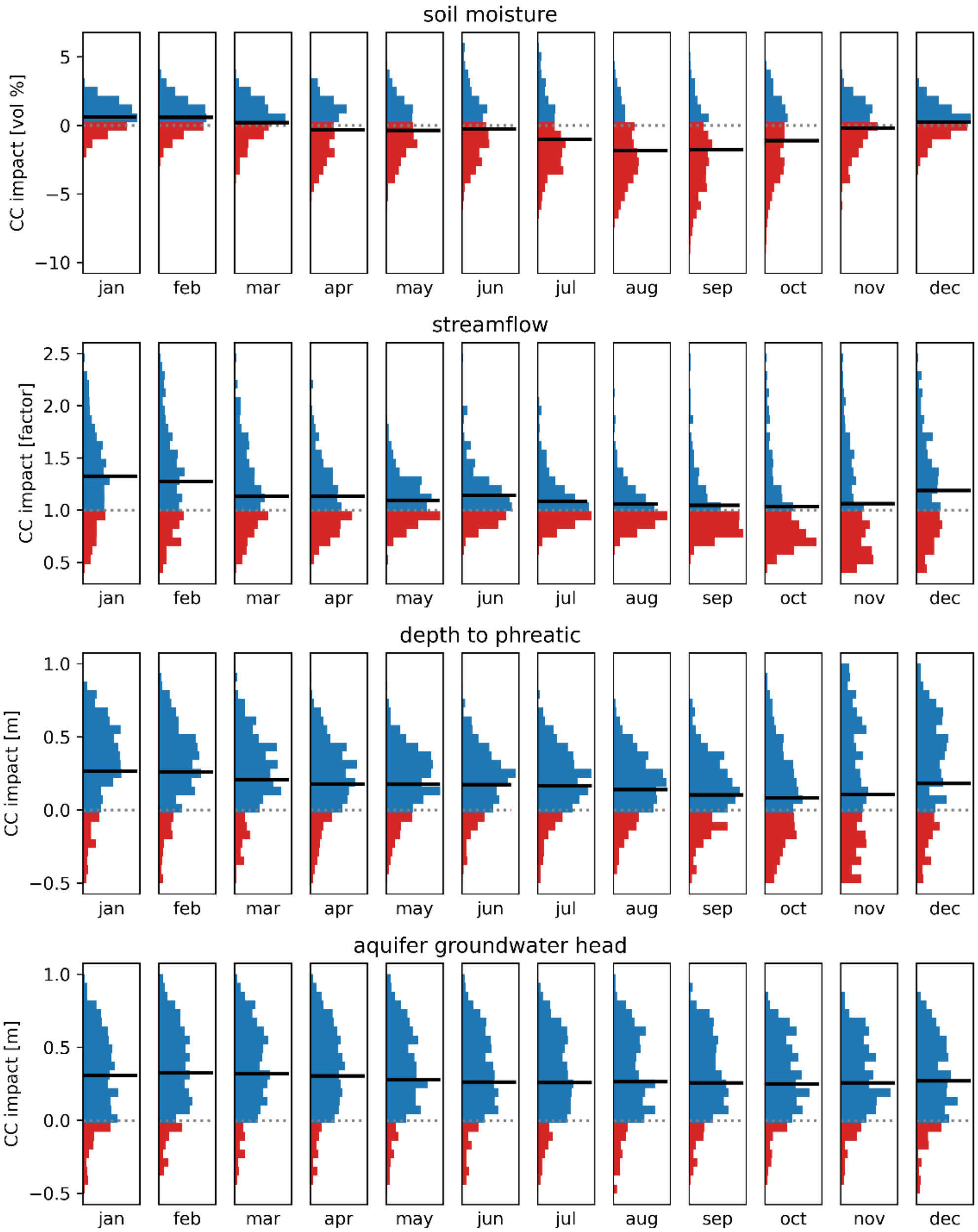

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**Figure 4:** **Predicted changes in key hydrological variables in Denmark from reference to end-century (17 climate models). The solid black line represents each month's and variable's median change across the climate models, as a mean for Denmark. The histograms show the spread of those mean changes across all 17 climate models and all 30 years of the end-century period.**

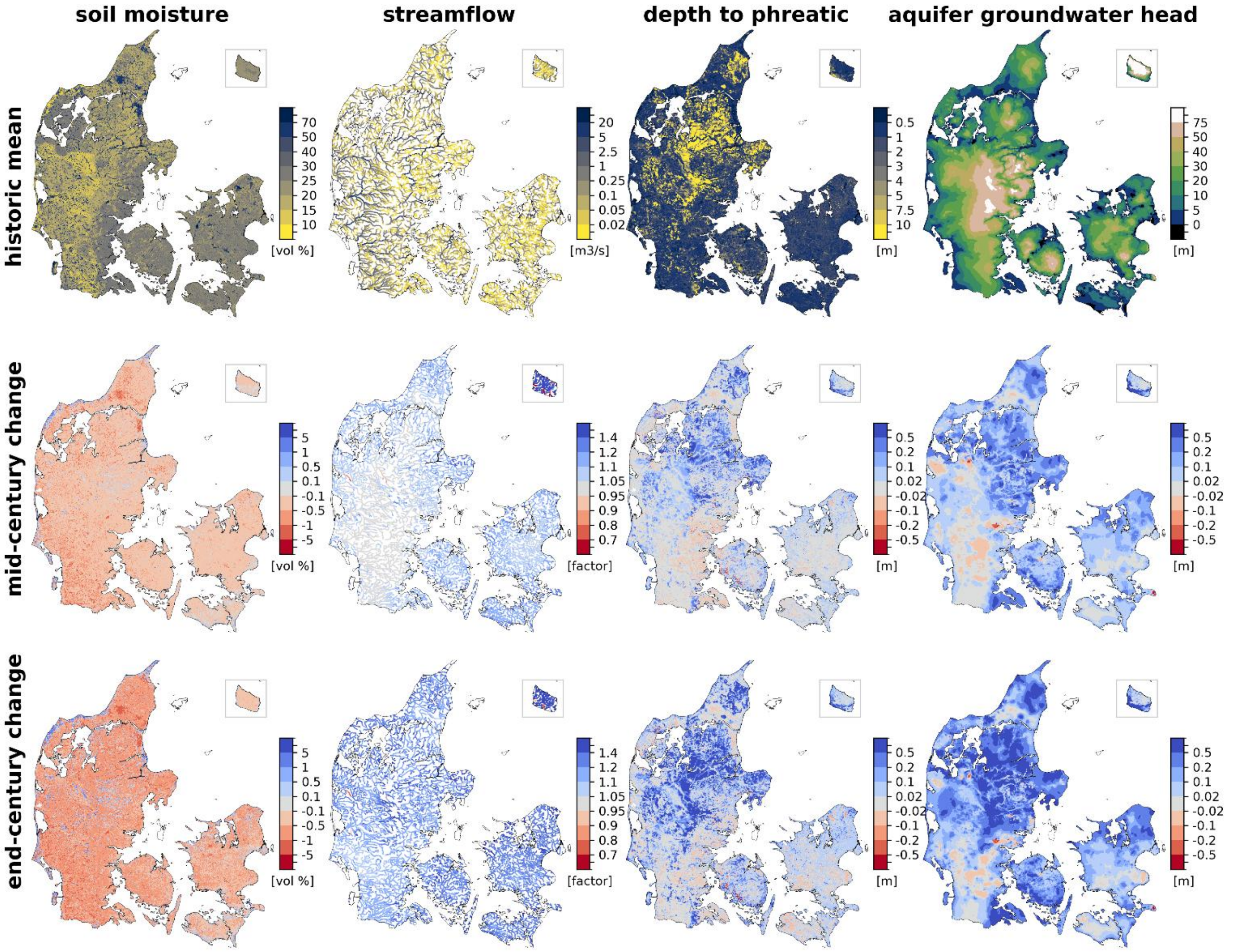

**Figure 5:** **Top row: Historic mean values simulated by the DK-model for soil moisture [vol. %], streamflow [m$^3$/s], depth to phreatic (below surface [m]), and the deeper groundwater head (mean of the two most important aquifer layers [m]). Middle and bottom row: Predicted change to each variable, as median across the 17 climate models for the mid-century and end-century period, respectively.**

### 4.2 Climate change predictions on changes in seasonality

As we can see from Fig. 3, Denmark expects an increase in climatic water balance seasonality, with the dry summer season becoming drier and the wet winter seasons becoming wetter. Even though in some ways the trend to wetter conditions is dominating, the seasonality change in itself is also reflected in the resulting hydrological response as simulated by the DK-model (Fig. 4). Figure 6 reveals that climate change impacts across the 17 climate models throughout the hydrological cycle actually agree more on the increase in seasonality than on the overall trend: The top row shows areas where climate model runs show an increase in soil moisture, streamflow, depth to phreatic or aquifer groundwater head in more than 75 % (13 out of 17) climate models in blue. A decrease in more than 75 % of climate models is marked in red, and inconclusive areas are grey. Moreover, areas with negligible median change are hatched. On yearly average values, large parts of Denmark show a decrease in soil moisture, with only a few exceptions, mostly in low-lying areas. For streamflow, where average streamflow is dominated by winter values (compare Fig. 1), climate models generally agree on an increasing trend. For groundwater, the picture is less clear: Most of the country experiences increased values in most climate models. However, significant exceptions exist, mostly in areas where the uppermost groundwater table is close to the surface (compare Fig. 4) and, hence, is more affected by increased summer evapotranspiration. The bottom row of Fig. 6 shows the same trend agreement, but for the change in seasonality calculated as maximum – minimum monthly values per year: Apart from for limited local exceptions, most climate model runs agree that seasonality is increasing – for all four hydrological variables – irrespective of their general increase or decrease.

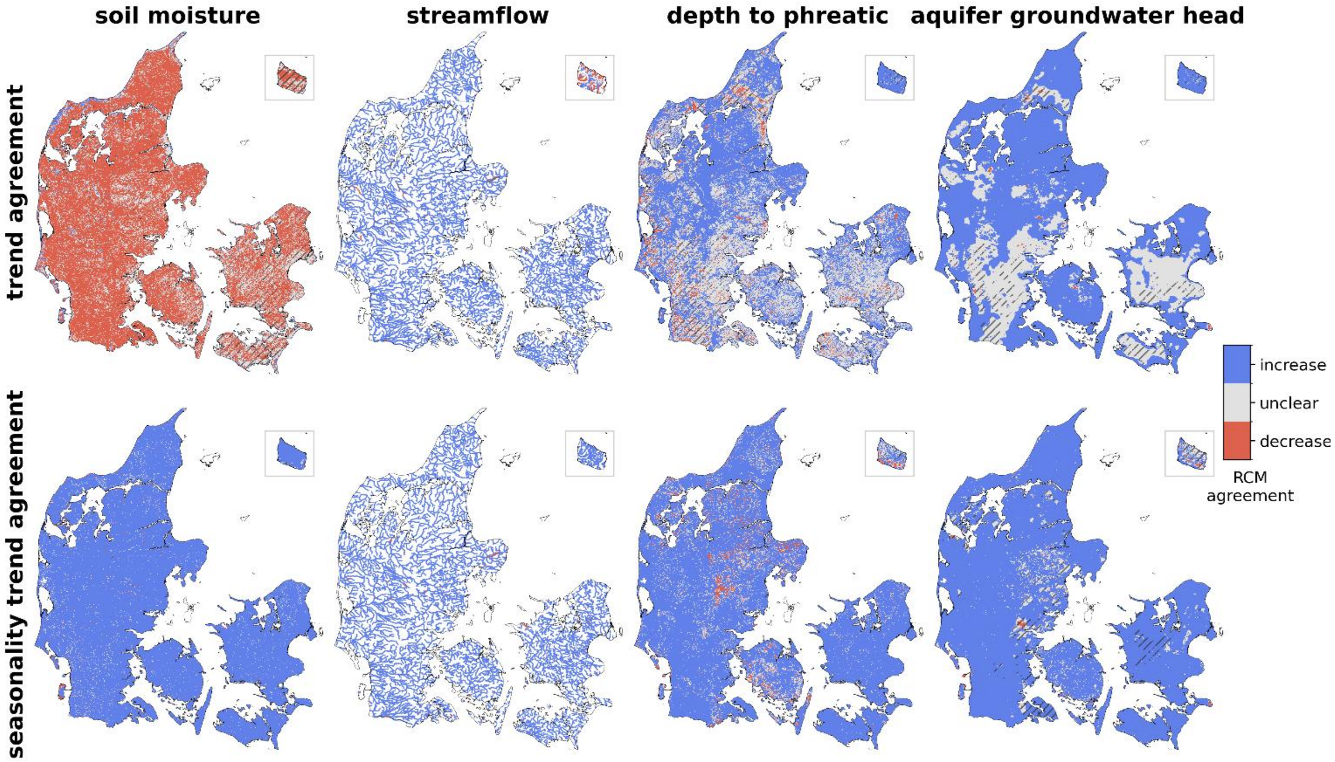

**Figure 6: Trend agreement across the 17 climate models. Top row: Trend agreement on climate change impact on average soil moisture, streamflow, depth to phreatic and aquifer groundwater head (red: more than 75 % of climate models show decrease, blue: more than 75 % of climate models show increase). Bottom row: Trend agreement on climate change impact on seasonality (max – min of monthly values per year). Areas with marginal median changes (soil moisture < +/-0.5 %, streamflow < 0.98/1.02, groundwater < +/-2 cm) are hatched. For changes to the end-century period.**

Table 2 summarizes these findings, reporting the percentage of area (or percentage of streamflow points) that show a clear positive or negative climate change impact on the overall variables and the variables' seasonality (rows "increase" and "decrease", bold values in the Table 2) for the median of the climate runs, with agreement on the sign across at least 75% of

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the climate runs. Separately, areas with positive or negative climate change, but without agreement across the climate models are reported (rows "increase unclear" and "decrease unclear"), as well as areas with only marginal climate change impact. Marginal climate change impacts are defined as soil moisture changes of less than 0.5 %, streamflow factor changes of less than 0.98 or 1.02, and groundwater changes of less than 2 cm. Here, values for both the end-century period are shown, as presented in Fig. 6, as well as values for the mid-century period. The respective mid-century map can be found in (Fig. B 4).

**Table 2: Percentage of area (or percentage of streamflow calculation points) that show marginal changes (soil moisture < +/-0.5 %, streamflow < 0.98/1.02, groundwater < +/-2 cm) or larger increases or decreases by climate change impacts on the average condition (columns "CC impact") or on the seasonality (columns "CC impact on seasonality"). Increases and decreases are separated into areas where 75% of climate models agree on the trend and the remainder ("unclear").**

| | | **mid-century** | | **end-century** | |
|---|---|---|---|---|---|
| | | **CC impact** | **CC impact on seasonality** | **CC impact** | **CC impact on seasonality** |
| **soil moisture** | marginal | 82.6% | 16.2% | 35.0% | 5.6% |
| | increase unclear | 0.6% | 2.0% | 1.9% | 1.0% |
| | decrease unclear | 1.4% | 0.3% | 2.5% | 0.4% |
| | increase | **1.4%** | **81.1%** | **3.0%** | **92.3%** |
| | decrease | **14.0%** | **0.4%** | **57.6%** | **0.7%** |
| **stream-flow** | marginal | 9.0% | 0.6% | 0.8% | 0.6% |
| | increase unclear | 34.0% | 2.9% | 1.1% | 0.0% |
| | decrease unclear | 0.3% | 0.0% | 0.0% | 0.0% |
| | increase | **56.5%** | **96.5%** | **97.9%** | **99.4%** |
| | negative | **0.3%** | **0.0%** | **0.2%** | **0.0%** |
| **depth to phreatic** | marginal | 48.5% | 11.6% | 30.4% | 4.3% |
| | increase unclear | 17.3% | 7.0% | 10.1% | 4.1% |
| | decrease unclear | 5.5% | 4.0% | 5.7% | 3.3% |
| | increase | **25.7%** | **75.8%** | **50.0%** | **84.8%** |
| | decrease | **3.1%** | **1.6%** | **3.9%** | **3.5%** |
| **aquifer ground-water head** | marginal | 19.7% | 38.2% | 10.0% | 12.7% |
| | increase unclear | 27.9% | 6.0% | 15.7% | 1.0% |
| | decrease unclear | 3.6% | 0.3% | 2.5% | 0.3% |
| | increase | **48.5%** | **55.2%** | **71.6%** | **85.7%** |
| | decrease | **0.4%** | **0.3%** | **0.3%** | **0.3%** |

## 4.3 Indices-based predictions

This change in seasonality is expected to also have an impact on extremes. One way of quantifying extremes is to use hydrological (drought) indices. Figure 7 shows the four indices *ESSMI*, *SDI*, $SGDI_{shallow}$ and $SGDI_{deep}$ together with the two meteorological indices *SPI* and *SPEI*. All indices were standardized for the reference period and then calculated for the future periods relative to the same climate model's reference period values. Hence, the expected value during the reference period is 0, and any future deviation from 0 indicates a change compared to the reference period. Displayed are then the average Denmark-wide values for each month during the two future periods as a median across the 17 climate models. *SPI* values, representing precipitation, slightly increase during most of the year, with decreases only observed during the months

July, August, and September. The trend to drier summers (and early autumn) is more pronounced in *SPEI*, representing climatic water balance. This change in climatic input, then, is most directly translated to reduced *ESSMI* values, indicating an increased tendency to soil moisture droughts. *SDI* (streamflow) and $SGDI_{shallow}$ (depth to phreatic) are less impacted by the drier summer climate, and show a slight delay compared to the meteorological input. Their general increase can be linked to the higher net precipitation during winter, resulting in higher recharge, which generally moves $SGDI_{deep}$ to wetter conditions, even though also here the increase during late winter and early spring is most pronounced.

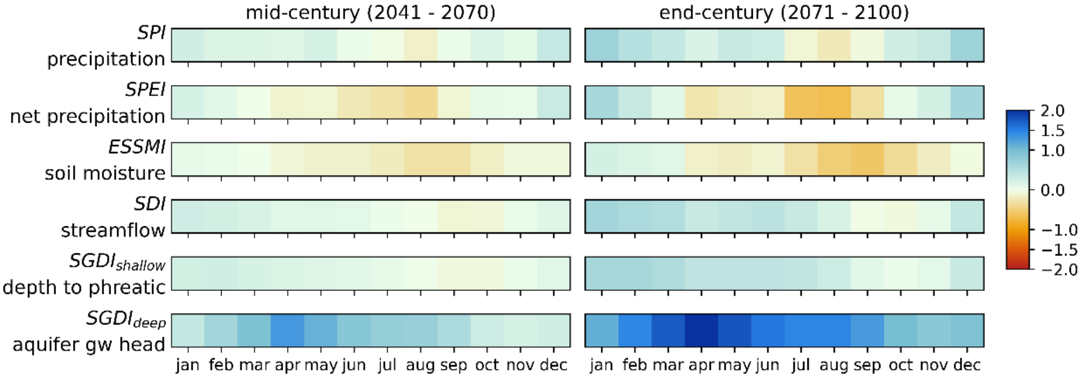
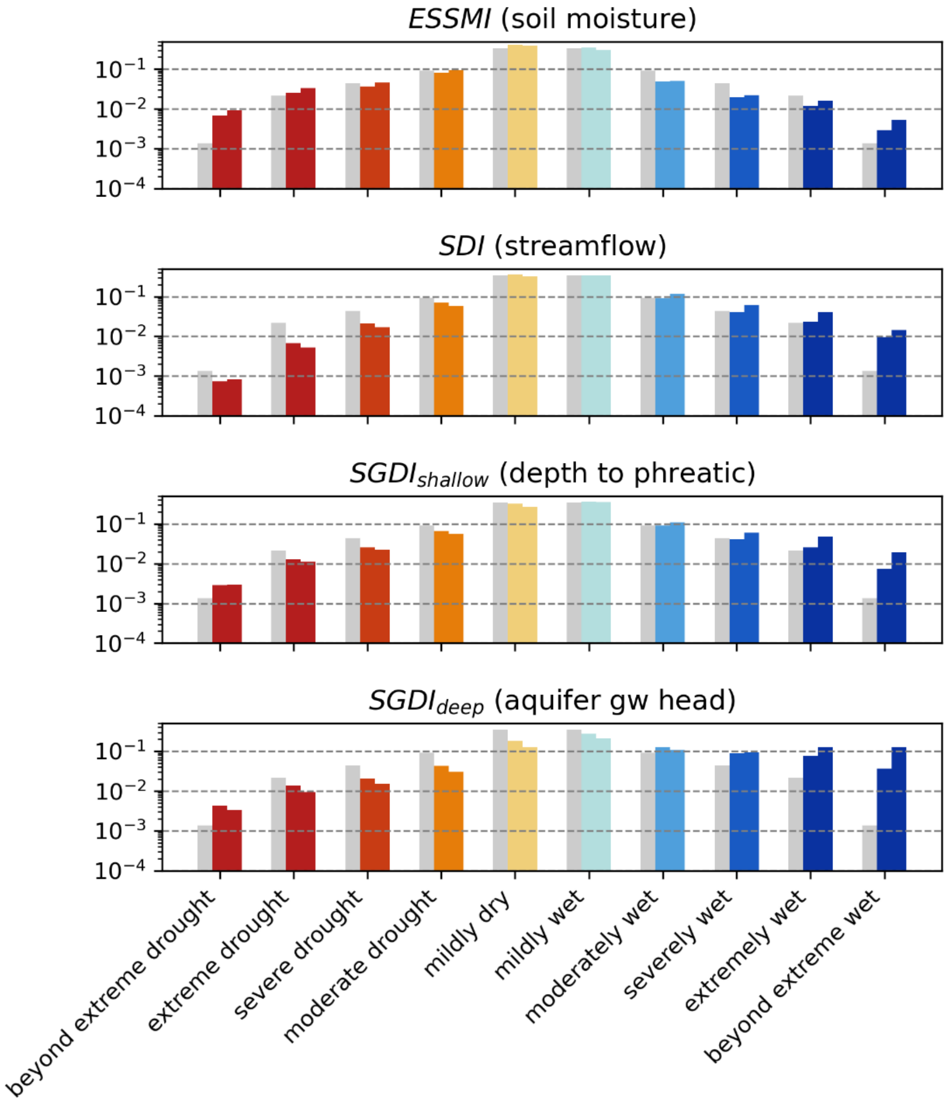


**Figure 7: Ensemble median drought values for the 17 climate models and the two investigated periods for all six indices. For the reference period, these values are expected to be 0 according to the standardizations applied. Hence, any deviation in the future periods from 0 indicates a change compared to the reference period.**

### 4.3.1 Frequencies of dry and wet anomalies

To not only look at average values across the period, but also investigate the occurrence of anomalies, Fig. 8 visualises the occurrence frequency of conditions above/below the defined thresholds of drought categories (compare Table 1) throughout Denmark. This reveals a large increase in extreme conditions, both on the dry and the wet end, for *ESSMI* values. The other compartments change to generally more wet conditions, with less frequent Denmark-wide droughts of different severities, and more frequent Denmark-wide wet conditions. The exception is beyond extreme droughts (<-3) for $SGDI_{shallow}$ and $SGDI_{deep}$, which also increase in frequency.



405 **Figure 8: Distribution of future frequencies of drought and wet events above specified thresholds (coloured) across the ensemble of 17 climate model runs. The grey bar of each group displays the expected frequency, whilst the second and third coloured columns of each group display mid-century and end-century frequencies, respectively.**

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### 4.3.2 Dry and wet severity

**Figure 9: Severity change for moderate wet/drought events (>1/<-1) to the end-century period: Values are wet/drought severities as percentage of the respective reference period values, as medians across the 17 climate models. Top row: Change of wet severity during winter (DJF). Bottom row: Change of drought severity during summer (JJA).**

Figure 9 shows the changes in drought severity, as well as wet condition severity, for the end-century period. Changes are calculated as the future severity relative to the respective reference period's severity, for the medians of the 17 climate models. The top row in Fig. 9 displays the changes to wet severity (defined as severity above the moderate threshold, +1) during the winter months December, January, and February. During this period, with generally highest climatic water balance surplus, conditions get even wetter across the entire hydrological cycle. This trend to wetter conditions during winter only sees larger exceptions for soil moisture, where there do exist areas, especially on Jutland, which experience a decreased wet severity for soil moisture. Those are linked to areas where the phreatic surface is deep (compare Fig. 5), far below the bottom of the root zone. Hence, the generally increasing groundwater levels cannot contribute to increased soil moisture. Instead, those areas are affected by increased evapotranspiration linked to increased temperatures. The bottom row in Fig. 9 displays changes to drought severity (defined as severity below the moderate threshold, -1) during the summer months June, July, and August. During this period, with generally negative climatic water balance, soil moisture droughts increase markedly across all of Denmark. The signal for the other compartments, however, is more heterogeneous: With increased (net) precipitation, groundwater levels generally rise. This also applies to the shallow groundwater table. Even though this rise of the shallow groundwater table is largest during winter (compare Fig. 4), it remains apparent during summer due to the lagged response of groundwater levels to precipitation (deficit) (Schneider et al., 2025), most apparent where shallow groundwater tables are deep, e.g. in central Jutland (compare Fig. 5). As streams in Denmark generally are groundwater-fed, higher groundwater levels impact streamflow – and are responsible for a decrease of moderate drought severity during summer across large parts of the country. The deeper groundwater rises most pronouncedly, and with more limited seasonality than the shallow groundwater table (compare Fig. 4). Some exceptions to a decrease of drought conditions during summer are visible, where moderate drought severity increases. Those patches are mostly linked to demand-driven irrigation implemented in the DK-model. Irrigation abstractions are, within some limits, based on current permits, allowed to increase in the model simulations in line with increased demand due to decreased soil moisture, and parts of the irrigation wells extract from deeper aquifers.

## 5 Discussion

### 5.1 Relation to previous studies

Climate models consistently show an increase in precipitation for parts of Northern, Central, and Western Europe (Jacob et al., 2014), as also reflected over Denmark (Seidenfaden et al., 2022). How future climate with increased precipitation translates into hydrological impacts is, however, heterogeneous both in space, time, and across hydrological compartments, as it also depends on the projected changes to temperature, evapotranspiration, and seasonality of meteorological variables. For example, increases in precipitation can be counteracted by increases in evapotranspiration, leading to diverse hydrological responses (Parry et al., 2024) at least during parts of the year, or such responses can be driven by changes in snow regimes (Nygren et al., 2020). Hence, climate change in these regions can lead to both increase or decrease (i) in groundwater recharge and levels dependent on region (Seidenfaden et al., 2022; Vergnes et al., 2023), (ii) in streamflow dependent on region and season (Lobanova et al., 2018; Meresa et al., 2023; Vergnes et al., 2023), (iii) in peak flows dependent on region (Lane et al., 2022), or (iv) in soil moisture dependent on region and season (Grusson et al., 2021). Also, complex especially in groundwater-dominated systems where response times vary strongly between compartments, complex interactions such as an increase of streamflow droughts whilst at the same time stable or decreasing groundwater droughts (Parry et al., 2024) are projected. Moreover, despite the general increase in precipitation, an increase in multi-year droughts can be expected (van der Wiel et al., 2022). Specifically for Denmark, ongoing work by Häberli et al. (2026a) is showing a pronounced increase in drought frequencies throughout meteorological and hydrological indices, based partly on the drought indices presented here, but also a larger ensemble of climate models.

Previous studies have acknowledged that the sensitivity of hydrological variables to changes in precipitation and evapotranspiration depends on season and hydrological compartment (e.g., Eisner et al., 2017; Hughes et al., 2021; Parry et al., 2024). For Northern, Central, and Western Europe, an increase in seasonality was also found, e.g., for groundwater levels in wetlands (Thompson et al., 2023), groundwater recharge (Hughes et al., 2021), or runoff (Poschlod et al., 2020). Parry et al. (2024) showed an increase in summer droughts for streamflow, with a diverging signal in groundwater where summer droughts were offset by wetter winters, similar to our results. Their results are based on separate modelling systems for groundwater and streamflow; ideally, the complex interplay of season and compartment across the hydrological cycle calls for integrated hydrological assessments (Mourot et al., 2025) such as in this study. However, many studies focus on single hydrological compartments. This is reflected in the most recent IPCC AR6 report (Caretta et al., 2022), which summarises state-of-the-art in studies of hydrological compartments, but has a limited focus on interlinkages between compartments and changes in seasonal patterns.

In our study for Denmark, the changes in seasonality across interlinked hydrological compartments were shown to have a stronger signal than changes in average conditions. Also, our study, combined with previous work by Schneider et al. (2025), revealed that the groundwater system in Denmark is crucial for understanding the interlinkages and changes in seasonality across the entire hydrological cycle. Here, we mainly focus on national tendencies and changes in seasonality in the overall hydrological signal. However, it is worth noting that regional differences in hydrological climate change responses across Denmark have been documented (Seidenfaden et al., 2022).

### 5.2 Limitations and uncertainties

Future assessment studies, such as the present, are underlaid with numerous uncertainty sources (Refsgaard et al., 2013) related to (i) climate forcing data e.g., emission scenarios and climate model uncertainty, downscaling and implementation, (Chan et al., 2021; Teutschbein and Seibert, 2013); (ii) hydrogeological interpretation, calibration and parameterisation (Her et al., 2019; Kim et al., 2024); (iii) model structure e.g., limitations in model code (Rebelo et al., 2025; Vansteenkiste et al., 2014); (iv) prediction capability e.g., parameter transferability (Broderick et al., 2016; Thirel et al., 2015); (v) assumptions of future societal trajectories e.g., future water use or land use practices (Olesen et al., 2019); (vi) method of analysis e.g., hydrological indices (Laimighofer and Laaha, 2022).

The uncertainty of climate model data, particularly the choice of global climate model, is well-known and documented. It can be substantial (Matte et al., 2019) and is often believed to overshadow many other uncertainty sources when dealing with quantitative hydrology (Refsgaard et al., 2016). For Scandinavia, it was also shown that fine-scale convection-permitting regional climate models show a distinct future drought signal (Häberli et al., 2026b).

An example of uncertainties arising from the implementation of climate data in hydrological models, also relevant here, is the choice of the PET formula. PET influences predicted future amounts of net precipitation, and, consequently, hydrological responses under climate change, especially important for summer drought prediction. Some hydrological studies found the uncertainties arising from different PET formulas to be small compared to the uncertainties from different global and regional climate models (Lemaitre-Basset et al., 2022; Williamson et al., 2016), whilst others found a more significant impact of the choice of PET formulas at least for low flow predictions (Dallaire et al., 2021; Koedyk and Kingston, 2016). Different PET methods rely on different combinations of meteorological variables and exhibit different sensitivity to changes in the input. In the present study, the projected amplification of hydrological seasonality and the emerging divergence between meteorological and hydrological anomalies are closely linked to increased evapotranspiration during summer. The here used temperature-driven PET formula (Oudin) may over- or underestimate absolute PET changes; however, the relative increase of PET under future climate seems to be a robust feature across different PET methods in temperate climates (Dallaire et al., 2021; Lemaitre-Basset et al., 2022). Consequently, the key findings regarding increased summer drying are expected to be qualitatively robust. Future work could assess the sensitivity of these results by comparing different PET formulations within the DK-model framework.

Climate change impacts on hydrology will result in significant societal adaptations, which again will have feedback to the hydrological system. In addition to the societal changes occurring as a response to climate change, other significant changes will occur due to socio-economic developments. E.g., the future land use and water management are substantial uncertainty factors that cannot be extrapolated with certainty. In this study, we assume no change in drinking water abstraction. Depending on the trajectory change in abstraction scenarios can however have a significant effect on impact assessments as shown by e.g., Rusli et al. (2024); however, in the Danish case these effects are likely to most important on local scale (see also Sect. 5.3). In this study, irrigation is demand-driven, i.e. it responds to changes in the climate alone, but there are no changes in land use management. In reality, it must be expected that future farming practices (e.g., crop types, tile drainage configuration, sowing and harvesting time, irrigated areas, irrigation systems, and more) will adapt to changes in future climate. A thorough analysis of combined socio-economic effects can be carried out using a Shared Socioeconomic Pathways (SSP) approach (Zandersen et al., 2019); however, this is beyond the scope of the present study.

### 5.3 Potential implications of the intensification of the hydrological seasonality

In this section, we reflect on the likely direct implications of climate change through impacts on hydrology, focusing on the intensification of the hydrological seasonality. Impacts are addressed for agriculture and the open landscape, and the urban environment, separately. We acknowledge that several of the impacts will lead to adaptation measures that will impact the hydrology in a feedback loop, however this is neither accounted for in our presented model analysis nor in the implications listed below.

#### 5.3.1 Agriculture and landscape

The agricultural sector will be affected by both the projected intensification of the hydrological system and by the parallel land transformation as part of the green transition.

**Wetter winters.** Increased streamflow and phreatic groundwater levels will amplify existing problems for farmers regarding waterlogging and wet fields in spring, with negative implications for sowing time and yield losses (Tian et al., 2021). Adaptation measures to counteract such issues are increased drainage, improving the discharge capacity of streams by embankments, or expansion/deepening of river cross sections. Wetter winters with increased drain flow will also reduce nitrate retention, since a smaller fraction of rootzone leaching will be reduced in the deeper groundwater (Motarjemi et al., 2023). Most adaptive measures to handle wetter winters are in direct conflict with ongoing national policies to transform river valleys and lowland organic soils by river restoration and rewetting to reduce nutrient loads and green-house gas emissions (Denager et al., 2026).

**Drier summers.** The increase of severe summer droughts will likely cause reduced yields and consequential economic losses, as seen during historical droughts such as 2018 and 2023 (Danmarks Statistik, 2018, 2023; Jensbye et al., 2025). To counteract such consequences, considerably more irrigation will be required, which will have negative impacts on low flows in streams and on groundwater-dependent ecosystems (Danapour et al., 2021). Possible positive implications of warmer summers could be longer growing seasons, where water is available. Alternative adaptive measures to irrigation could be shifts in crop type or variety and growing season to improve drought resistance. In a warmer climate, surface water systems are more vulnerable to eutrophication caused by agricultural nutrient loads. In addition, there is concern that summer droughts will increase leaching of nitrate, due to a surplus caused by low plant uptake of applied fertilisers (Blicher-Mathiesen et al., 2021, 2025) particularly in connection with succeeding large precipitation events (Raij-Hoffman et al., 2024).

### 5.3.2 Urban climate adaptation and water supply

The impacts on the urban environment caused by climate change and intensification of the hydrological system are mainly attributed to increased flood risks; however, impacts of drought can also be seen in water demand and infrastructure damages.

**Wetter winters.** Increased streamflow and urban runoff pose an imminent challenge for urban surface water systems and sewers, and this has been the focal point in past climate adaptation in Denmark. Recently, flooding and damage by elevated groundwater levels in urban areas have received increasing attention, and both flooding from surface and groundwater are considered major challenges that are projected to increase with climate change (Liu et al., 2026; Rasmussen et al., 2023). From a quantitative groundwater perspective, climate change is projected to increase the resource for drinking water and could potentially alleviate issues regarding negative impacts on stream baseflow; however in Denmark, sustainable groundwater resources are generally limited by water quality constraints (Danish Environmental Protection Agency, 2023; Henriksen et al., 2024; Jørgensen et al., 2024).

**Drier summers.** Despite increased frequencies of summer droughts, the quantitative groundwater resource is not expected to be reduced, since groundwater is recharged during winter, which is projected to get wetter.

However, during summer droughts, domestic water demands have been reported to increase substantially, leading to pressure on the supply network due to limited capacity and ultimately invoking restrictions on consumption (HOFOR, 2025). Such instances will likely increase in frequency due to climate change and, combined with population migration to urban centres and increasing demands from new industries (e.g., Power-to-X) lead to increasing pressure on urban water supply in the future (Danish Environmental Protection Agency and NIRAS, 2023). Another consequence of summer drought is land subsidence and shrinking of clay soils, leading to infrastructure damage such as subsidence damage and settlement cracks in buildings and roads. This has been shown to be correlated to drought indices on soil moisture and shallow groundwater (Seidenfaden et al., 2025).

## 6 Conclusion

This study assessed how projected climate change under RCP8.5 propagates through the interconnected hydrological system of Denmark using the integrated, physically based National Hydrological Model (DK-model). By combining multi-model climate projections (17 EURO-CORDEX simulations) with standardized hydrological indices (*ESSMI*, *SDI*, *SGDI*), we evaluated not only changes in mean conditions, but in particular changes in seasonality, and drought/wet severity across soil moisture, streamflow, shallow groundwater, and deep groundwater.

The main conclusions are: Climate change in Denmark is generally characterized by a shift to wetter conditions. However, embedded in this is a clear intensification of the hydrological cycle characterized by increased seasonality. Across the climate projection ensemble, there is even greater agreement on the changes (increases) in seasonality than on the changes in mean conditions. The increased seasonality of the hydrologic cycle is caused by an increased seasonality in climatic water balance. The heterogeneous propagation of this signal throughout the hydrological cycle depends on interlinkages and response times, where faster responding compartments (soil moisture) mirror the amplified summer drying most directly, while slower responding compartments (streamflow and especially groundwater) integrate and redistribute seasonal forcing. Beyond the increased seasonality towards wetter winters and drier summers, there is a tendency – at least locally – to increased drought severities across all seasons.

This study contributes to the climate impact literature by demonstrating that seasonal amplification can constitute a more robust climate signal than changes to mean conditions, and providing a national-scale, integrated assessment across interconnected hydrological compartments in a groundwater-dominated system. Future research should explore feedback from adaptive land and water management, investigate how intensified seasonality interacts with multi-year drought persistence, and new climate model projections.

The projected amplification of hydrological seasonality has important implications for climate adaptation: Increased groundwater recharge may enhance long-term water resource availability; however, there is a concurrent intensification of summer soil moisture droughts, increasing irrigation demand. Such seasonal asymmetry may exacerbate trade-offs between flood management, ecological requirements, groundwater abstraction, and nutrient mitigation strategies. Thus, adaptation planning in Denmark should not only prepare for a wetter future, but rather for a hydrological regime with stronger intra-annual contrasts and enhanced variability.

## Appendices

585 ## Appendix A: Climatic water balance

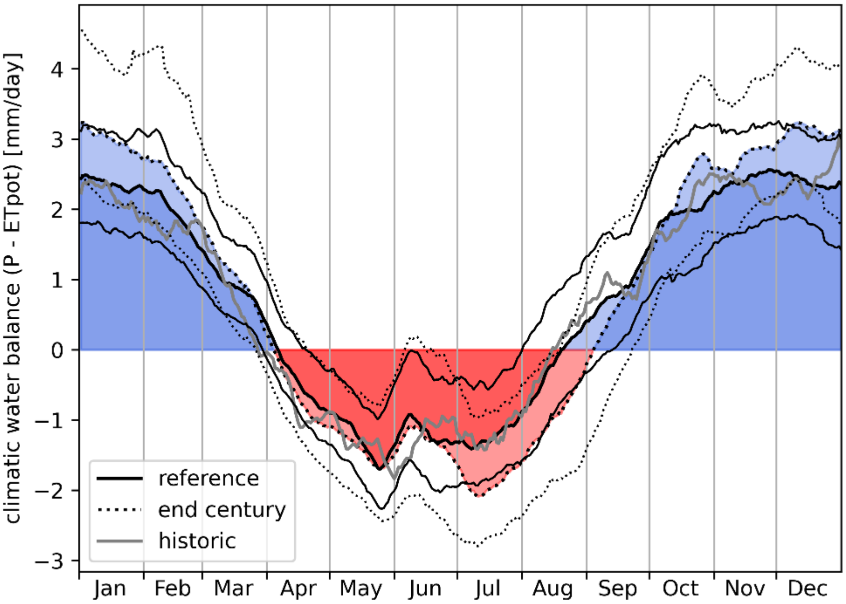

**Figure A 1: Climatic water balance (precipitation – PET). Mean across Denmark of the median of the 17 climate models. Based on values for each day of year for the reference (1991-2020) and end-century (2071-2100) period, with a 15-day moving average. As Fig. 3, but including (i) the 15-day moving average climatic water balance based on observed climate data during the historic 590 period 1991 to 2020 in grey and (ii) the 10 % and 90 % intervals across the 17 climate models and 30 years each for the reference and end-century period as thinner lines.**

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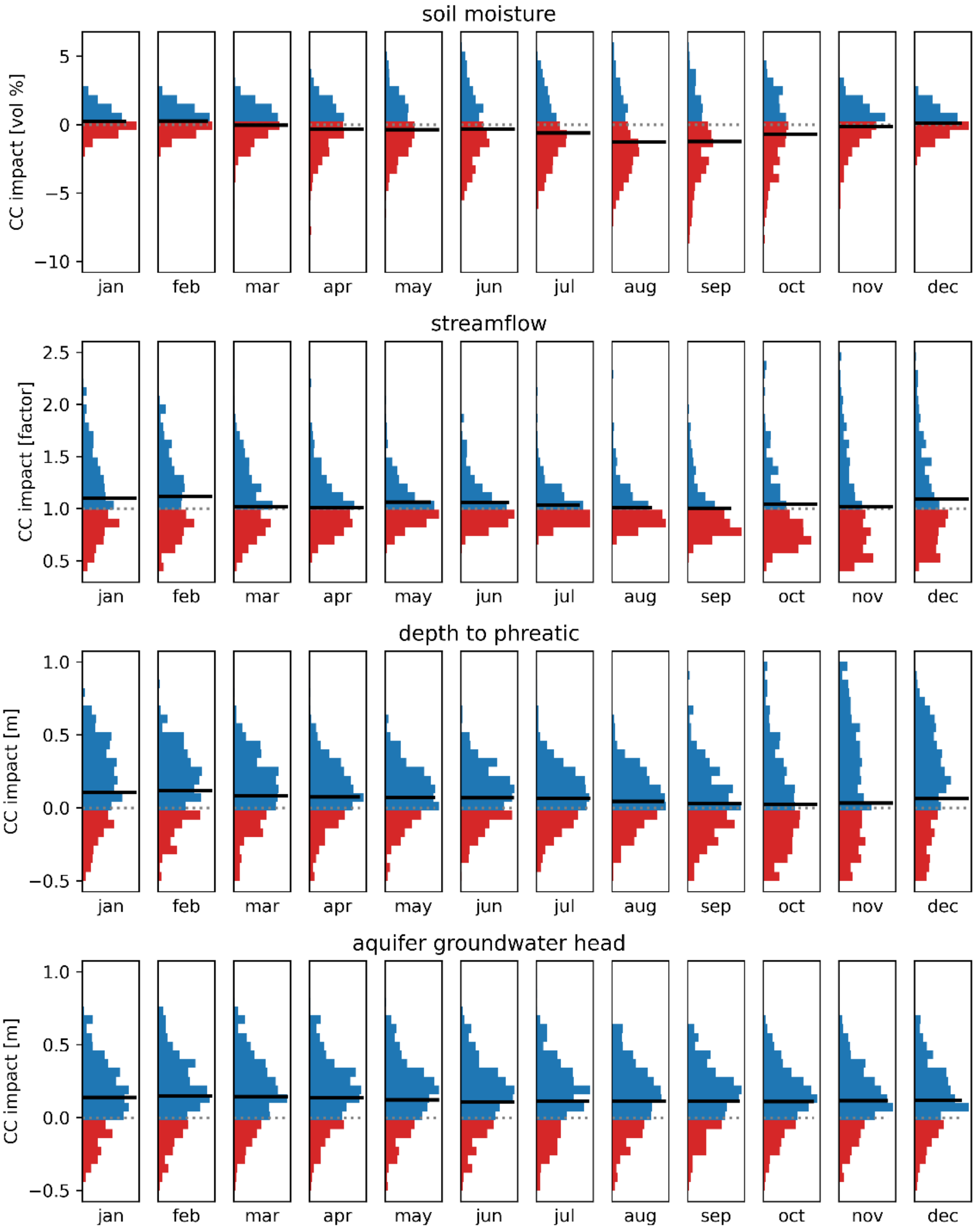
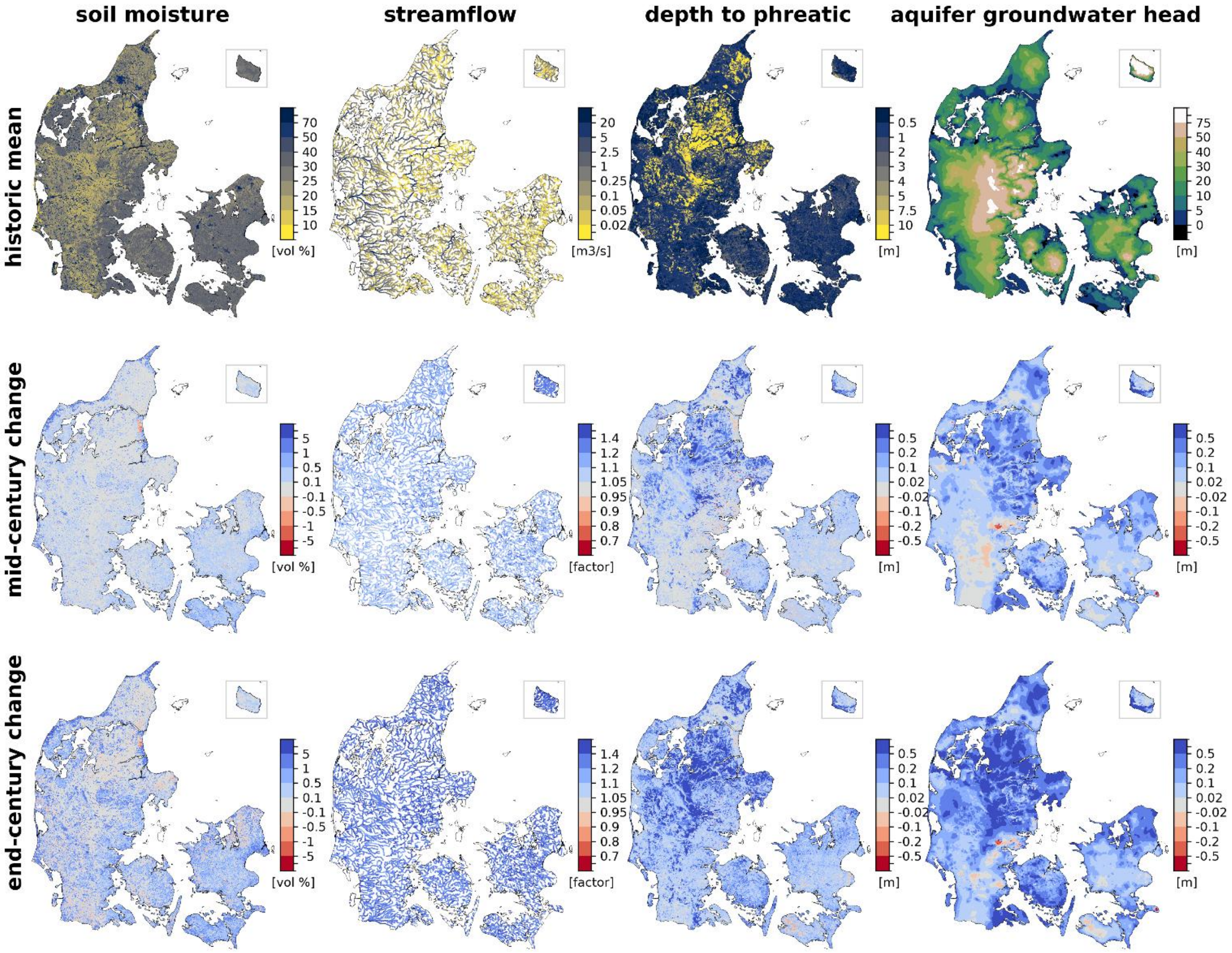
## Appendix B: Overall future hydrological signal



595 **Figure B 1: Predicted changes in key hydrological variables in Denmark from reference to mid-century (17 climate models). Equivalent to Fig. 3, but for different period. The solid black line represents each month's and variable's median change across the climate models, as a mean for Denmark. The histograms show the spread of those mean changes across all 17 climate models and 30 years of the mid-century period.**



600 **Figure B 2: Equivalent to Fig. 5, but for winter season (DJF). Top row: Historic mean values simulated by the DK-model for soil moisture [vol %], streamflow [m$^3$/s], depth to phreatic (below surface [m]) and the deeper groundwater head (mean of the two most important aquifer layers [m]). Middle and bottom row: Predicted change to each variable, as median across the 17 climate models for the mid-century and end-century period, respectively.**

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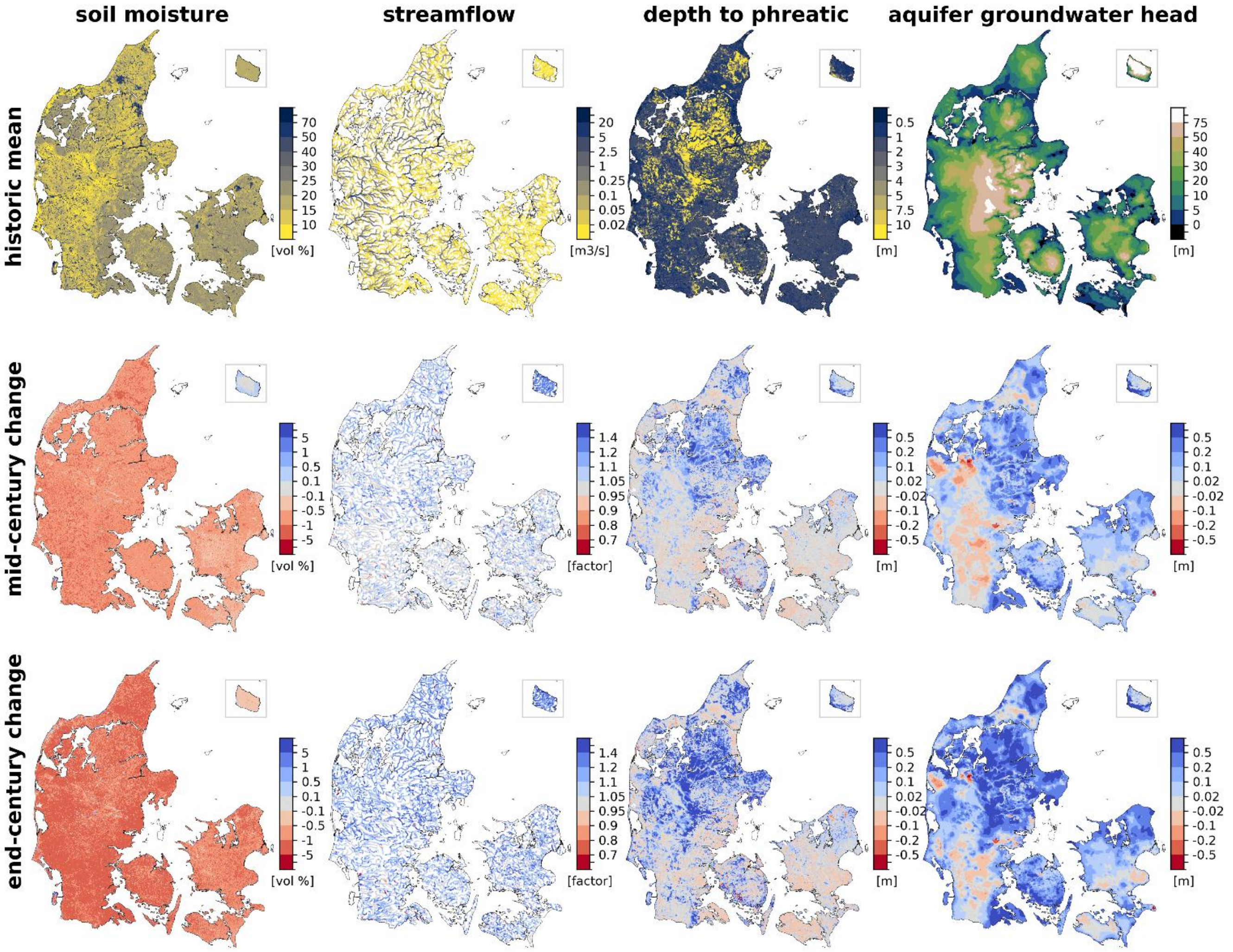

**Figure B 3: Equivalent to Fig. 5, but for summer season (JJA). Top row: Historic mean values simulated by the DK-model for soil moisture [vol %], streamflow [m$^3$/s], depth to phreatic (below surface [m]) and the deeper groundwater head (mean of the two most important aquifer layers [m]). Middle and bottom row: Predicted change to each variable, as median across the 17 climate models for the mid-century and end-century period, respectively.**

https://doi.org/10.5194/egusphere-2026-1531
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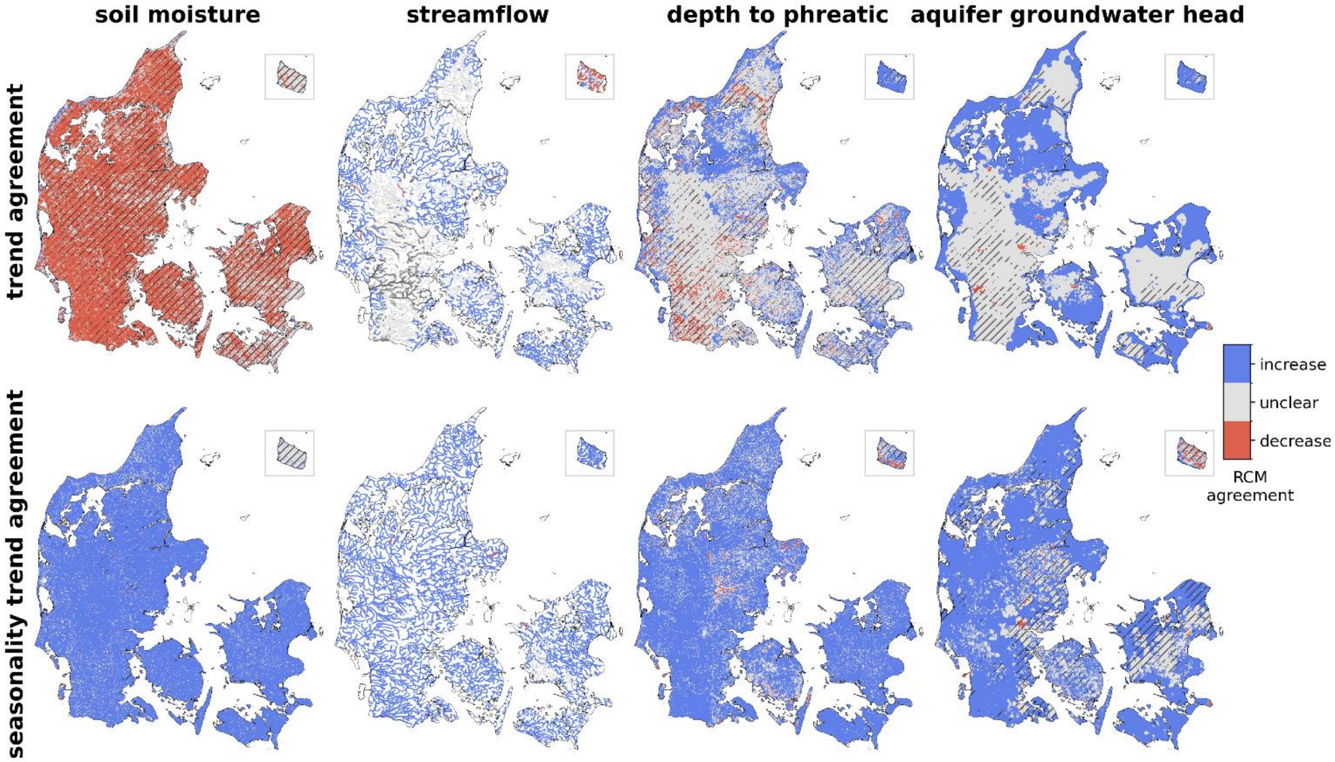

610 **Figure B 4: Trend agreement across the 17 climate models. Top row: Trend agreement on climate change impact on average soil moisture, streamflow, depth to phreatic and aquifer groundwater head (red: more than 75 % of climate models show decrease, blue: more than 75 % of climate models show increase). Bottom row: Trend agreement on climate change impact on seasonality (max – min monthly values per year). Areas with marginal median changes (soil moisture < +/-0.5 %, streamflow < 0.98/1.02, groundwater < +/-2 cm) are hatched. Same as Fig. 6, but for the mid-century period.**

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## Appendix C: Dry and wet severity

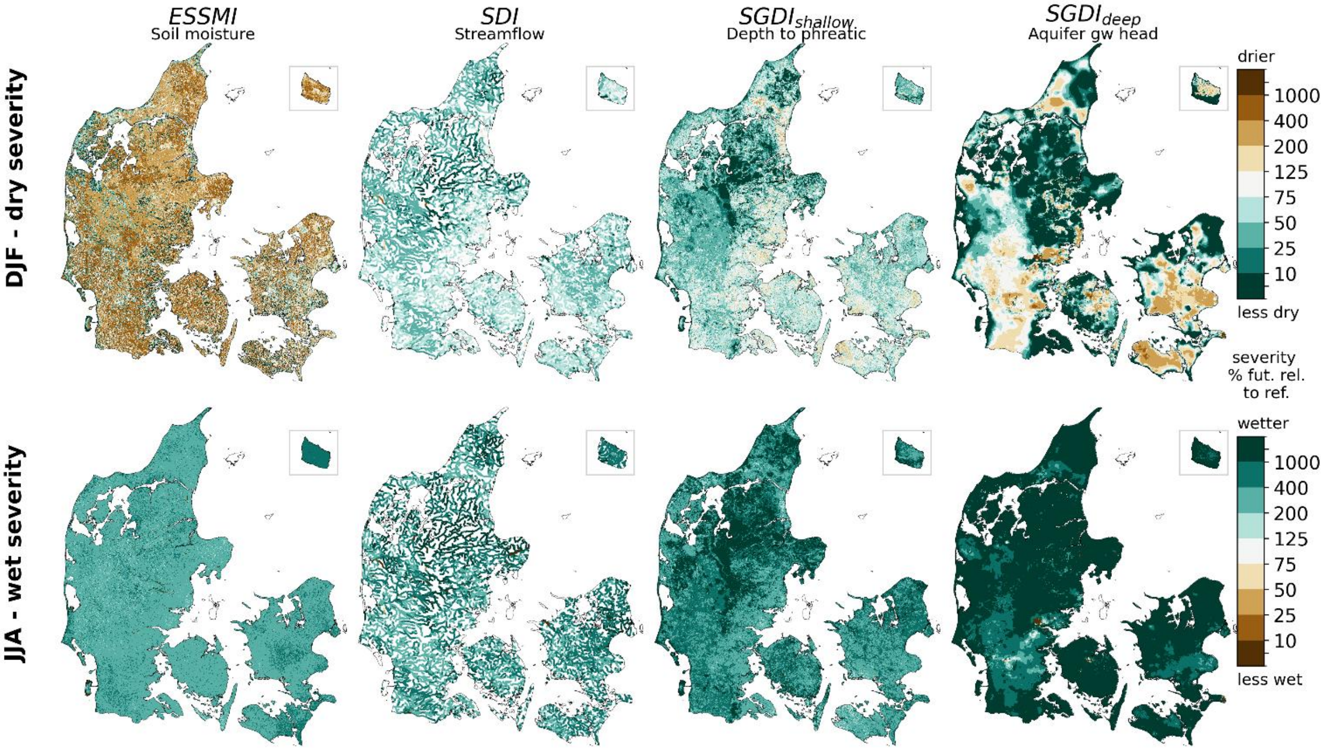

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**Figure C 1: Severity change for moderate wet/drought events (>1/<-1) to the end-century period: Values are wet/drought severities as percentage of the respective reference period values, as medians across the 17 climate models. Top row: Change of wet severity during DJF (winter). Bottom row: Change of drought severity during JJA (summer). Equivalent to Fig. 9, but for droughts during winter and wet conditions during summer instead.**

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**Figure C 2: Severity change for extreme wet/drought events (>2/<-2) to the end-century period: Values are wet/drought severities as percentage of the respective reference period values, as medians across the 17 climate models. Top row: Change of wet severity during DJF (winter). Bottom row: Change of drought severity during JJA (summer). Equivalent to Fig. 9, but for extreme instead of moderate thresholds.**

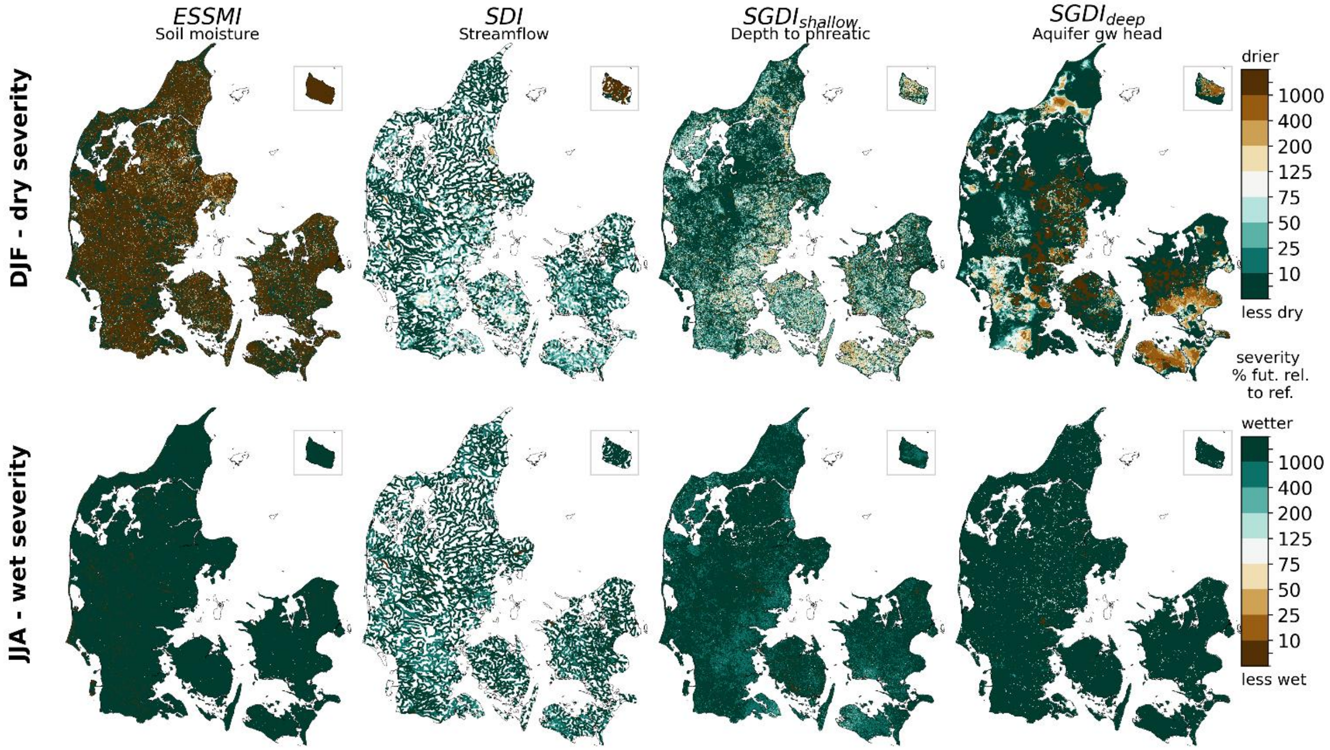

**Figure C 3: Severity change for extreme wet/drought events (>2/<-2) to the end-century period: Values are wet/drought severities as percentage of the respective reference period values, as medians across the 17 climate models. Top row: Change of drought severity during DJF (winter). Bottom row: Change of wet severity during JJA (summer). Equivalent to Fig. 9, but for droughts during winter and wet conditions during summer, and for extreme instead of moderate thresholds.**

## Data availability

The climate change impacts described here on soil moisture, streamflow, and the depth to phreatic surface are openly available via the Hydrologic Information and Prognosis System HIP hosted by Climate Data Agency (KDS) under https://hip.dataforsyningen.dk/. The same applies to the bias-corrected climate models used as forcing of the hydrological projections. Moreover, drought indices (in real-time) are shown on the same platform. The DK-model setup in the version reported here can be accessed in a repository under https://dataverse.geus.dk/dataverse/DKmodelHIP. All python scripts used to calculate the climate change impacts and drought indices, as well as the resulting data will be provided upon request to the authors without undue reservation.

## Author contributions

All authors contributed to the definition of the research aims. SST, IKS and RS developed the methods, with inputs from LTR and JCR – building on a body of work of a larger group of people working on the DK-model. RS prepared plots and maps visualizing the results. The manuscript draft was written by RS, SST and IKS; all authors reviewed and edited the manuscript. IKS was responsible for project administration during the current part of the work.

## Competing interests

The authors declare that they have no conflict of interest.

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