Journal of Hydrology: Regional Studies 60 (2025) 102507

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Modelling the impacts of climate change on groundwater recharge patterns in northern Germany

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ARTICLE INFO

Keywords:
mGROWA
Schleswig-Holstein
Climate ensemble
Representative concentration pathways

ABSTRACT

Study region: Schleswig-Holstein, Germany

Study focus: For water management and planning purposes, predictions of how groundwater recharge regimes are expected to change under climate change are of high importance. The northern German state of Schleswig-Holstein has a heavy reliance on groundwater resources, and is expected to experience both increasing precipitation and potential evapotranspiration rates in the future. We implemented the high spatio-temporal deterministic mGROWA hydrological model (100 m, daily) under the full climate ensemble recommended for use in Germany (44 members) until the end of the 21st century to simulate future groundwater recharge changes. For evaluation of climate change impacts, 30-year periods were used.

New hydrological insights for the region: The majority of the climate models show an increase in groundwater recharge rates over the periods 2041–2070 and 2071–2100. This is the case for all three evaluated RCPs (RCP2.6, RCP4.5 and RCP8.5); however, the increases are generally relatively small, with none of the changes classified as significant under the applied robustness test. We also implemented the "climate railguards" concept, which classifies the likely changes as the range between the 15th and 85th percentiles of the climate model results belonging to each RCP. Lastly, a comparison of the application of different spatial areas used for aggregation of results highlights the importance of selecting spatial units appropriate to the water management application.

1. Introduction

Estimates of groundwater recharge rates provide key information for various water management issues, such as the provision of municipal, agricultural and industrial water supplies, while ensuring that the abstraction rates remain at a sustainable level (Alley et al., 1999; Singh, 2014). It is therefore of high importance to be able to ascertain how groundwater recharge rates are expected to change as a result of climate change. In northern Germany, where the study area of Schleswig-Holstein is located, climate models tend to suggest both increasing rates of evapotranspiration, due to increasing temperatures, as well as a general increase in mean annual

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https://doi.org/10.1016/j.ejrh.2025.102507
Received 24 January 2025; Received in revised form 2 June 2025; Accepted 3 June 2025
Available online 10 June 2025

precipitation (Huang et al., 2015; DWD, 2021; Wunsch et al., 2022). Where these counteracting drivers occur, there remains uncertainty as to whether they will likely lead to increased or reduced groundwater recharge rates.

To simulate groundwater recharge rates, there are three broad modelling methods: lumped water balance models, distributed process-based models, and data-driven models (Atawneh et al., 2021). The North German Plain landscape presents a challenge for modelling groundwater recharge, due to: i) vast areas with near-surface groundwater (LLUR, 2017); ii) large areas of artificially drained agricultural land (Tetzlaff and Kuhr, 2011); and iii) thick low-permeability layers mostly consisting of Saalian and Weichselian till, partially with glaciolacustrine silt and clay (referred to hereafter as "*till layers*"; Kunkel and Wendland, 2020). The use of distributed process-based models allows for the interplay of highly heterogeneous site parameters to be adequately considered in the modelling of groundwater recharge (Secci et al., 2024), making them a suitable model type for this case study of Schleswig-Holstein.

For climate impact studies, it is common to consider ensembles of individual climate models, which typically include multiple models for each Representative Concentration Pathways (RCP). Through the implementation of ensembles, a large range of expected changes in the climatic variables over a region can be covered (Tebaldi and Knutti, 2007). For regional studies it is common to use regional climate models (RCMs), which have a higher spatial resolution than that of the general circulation models (GCMs) that are used as boundary inputs (Giorgi, 2019).

For practical planning purposes, the results of ensembles can be difficult to interpret, as they may deliver results for groundwater recharge estimates (or other hydrological outputs) that cover a large range, with the different ends of the spectrum suggesting that different planning responses be taken. For this reason, some interpretations of ensemble results consider robustness criteria (e.g., Pfeifer et al., 2015), some consider temperature thresholds of global warming levels (e.g., Jing et al., 2020), while others remove outliers from modelling results to provide a range of likely change (e.g., Linke et al., 2024).

Listed in Table 1 are studies that have modelled groundwater recharge under climate change over areas that include or are geographically near to Schleswig-Holstein. These studies incorporate various emissions scenarios, climate models, and hydrological models to predict groundwater recharge, with some based on the now outdated Special Report on Emissions Scenarios (SRES). The two

Table 1
Summary of relevant studies that have assessed groundwater recharge under climate change over areas including or close to Schleswig-Holstein.

Study	Region	Climate models	Hyd. model	Relevant results
(Hattermann et al., 2008)	German part of the Elbe catchment	100 downscaled climate realisations of GCM ECHAM4-OPYC3 (SRES A1)	SWIM	Median decrease of 22 % in groundwater recharge for 2051–2055.
Hiscock et al. (2011)	Five European catchments (excludes Germany)	4 GCMs (HadCM3, CGCM2, CSIRO2 & PCM) from SRES scenario A1F1	Unnamed soil moisture balance model	Generally increasing groundwater recharge in northern Europe and decreasing in southern Europe.
Neukum and Azzam (2012)	Catchment in Black Forest, Germany	The RCM REMO-UBA, with one climate model for each of the A1B, A2 and B1 emission scenarios	WaSim-ETH	Continuous decline in groundwater recharge in the summer months, which is sometimes, but not always, compensated for by an increase in groundwater recharge in the winter months.
Herrmann et al. (2017)	North Rhine-Westphalia, Germany	13 realisations of 2 RCMs (REMO UBA & WETTREG2010) belonging to one GCM (ECHAM5/MPI-OM) and 3 SRES scenarios (A1B, A2, B1)	mGROWA	No clear changes in groundwater recharge rates simulated.
Jing et al. (2020)	Nägelstedt catchment, Germany	Five GCMs (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESMCHEM & NorESM1-M) under three RCPs (2.6, 6.0 & 8.0)	mesoscale Hydrologic Model (mHM) and the groundwater model Open-GeoSys	Slight increase in groundwater recharge, which is greater under smaller temperature increases.
Herrmann et al. (2021a)	Lower Saxony, Germany	Reduced selection of the DWD reference ensemble v2018 (37 members of the 44)	mGROWA	A relatively small increase in groundwater recharge is simulated for most ensemble members, though the changes are not classified as significant.
Wunsch et al. (2022)[a]	Germany	DWD core ensemble v2018 (subset of 17 members of the full DWD ensemble v2018)	Machine learning approach based on convolutional neural networks	For the seven locations modelled in Schleswig-Holstein, groundwater level is predicted to decrease under the RCP8.5 scenario, while for the RCP2.6 and RCP4.5 scenarios, most climate models showed no significant changes.
Kumar et al. (2025)	Europe	5 GCMs (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM & NorESM1-M) for three RCPs (2.6, 6.0 & 8.5)	Four models: mHM, Noah Multi Physics model, PCRaster GLOBal Water Balance model & Variable Infiltration Capacity model	A strong north-south gradient in groundwater recharge is simulated across Europe, with decreases Southern Europe and increases in Northern Europe. Areas where the changes are close to zero are located in the mid-latitude region of Germany, with slight increases (< 10 %) predicted over Schleswig-Holstein.

a: Simulates groundwater level instead of groundwater recharge.

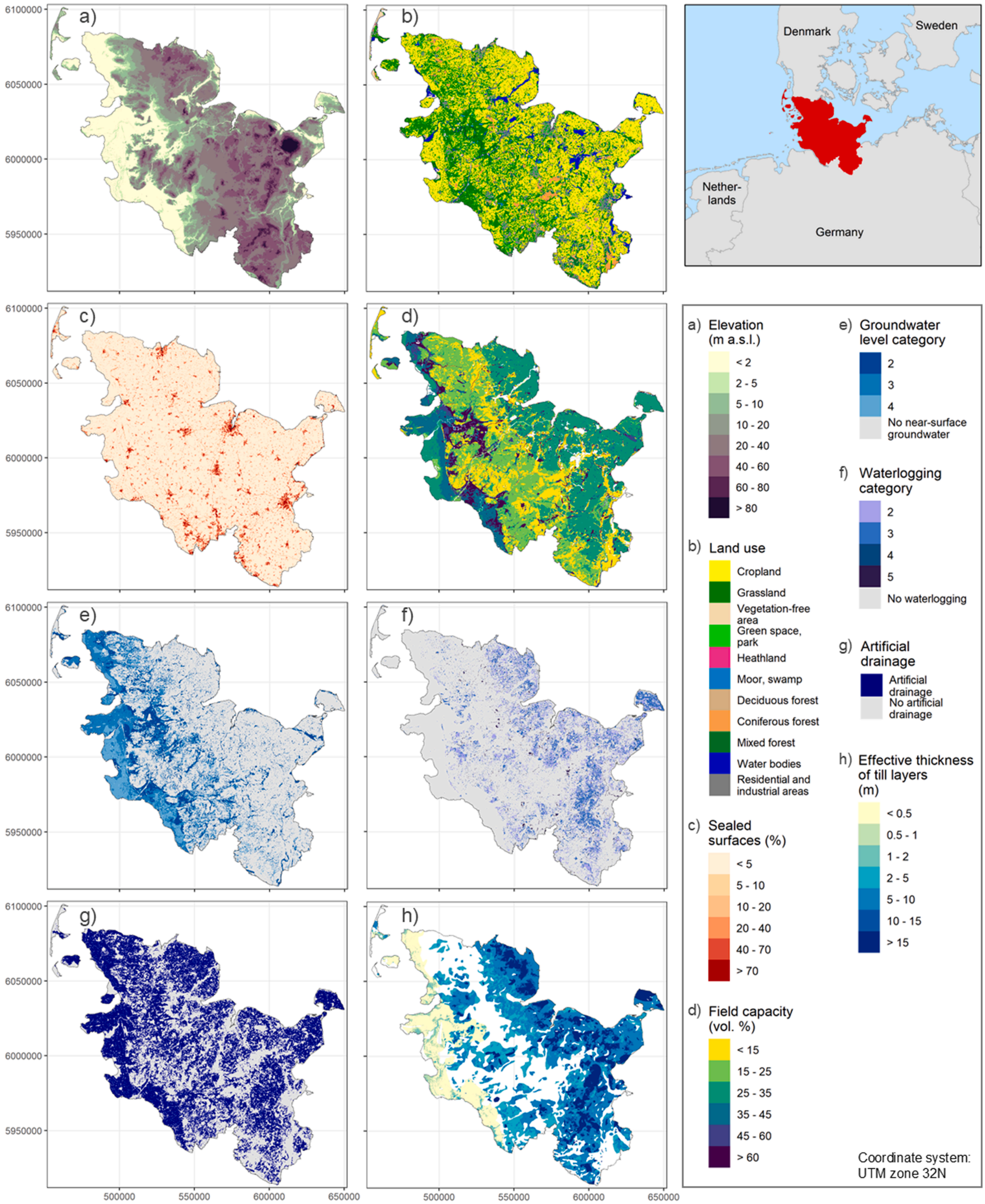

Fig. 1. Key input layers for the mGROWA hydrological model for Schleswig-Holstein: a) elevation; b) land use; c) surface sealing; d) mean field capacity over the upper 2.10 m; e) groundwater level category; f) waterlogging categories; g) artificially drained areas; and h) effective thickness of till layers. For modelling the climate projections until 2100, all model inputs presented in this figure are assumed to remain static. The location of Schleswig-Holstein is shown in the top-right.

listed studies that cover large spatial scales predict a strong pattern of increased groundwater recharge in northern Europe and a decrease in southern Europe (Hiscock et al., 2011; Kumar et al., 2025). The other six studies listed cover some or all of Germany, and exhibit results varying from increases to decreases in groundwater recharge rates.

The aim of this study is to quantify the expected changes in groundwater recharge patterns due to climate change in the northern German state of Schleswig-Holstein, using the full ensemble of climate models that the German Meteorological Service (DWD) recommends (DWD, 2021, 2023). For this purpose, the fully distributed, process-based mGROWA hydrological model (Herrmann et al., 2013, 2015) was implemented, and evaluation periods of 2041–2070 and 2071–2100 were selected, with analyses undertaken at the whole state level as well as at spatial planning scales used for groundwater resources management by the state's ministry. The specific study questions are:

- Can the mGROWA hydrological model be used to adequately model historical groundwater recharge rates in the hydrogeologically complex region of Schleswig-Holstein?
- How is climate change expected to alter groundwater recharge patterns in the state?
- How can the selection of evaluation areas used for the aggregation of modelling results influence groundwater management decisions?

2. Study area and data

2.1. Study area

The German state of Schleswig-Holstein is located in northern Germany, sharing land borders with Denmark and the German states of Lower Saxony, Hamburg and Mecklenburg-Vorpommern, as well as having coastlines along both the North Sea and Baltic Sea (shown on top-right of Fig. 1). It covers an area of approximately 15,800 km^2, and is classified as "temperate, no dry season, warm summer" (Cfb) under the Köppen-Geiger climate classification (Beck et al., 2018).

Schleswig-Holstein is part of the northern and central German unconsolidated rock area. The geology is mostly characterised by glacigenic (till) and meltwater deposits of the Saalian and Weichselian glaciation, while the coastal region next to the North Sea is dominated by tidal marine and coastal sediments (Beer et al., 2016). The state has sufficient precipitation to sustain large areas of rainfed crops (Destatis, 2021), and most runoff generation and groundwater recharge occurs over the winter months (Wunsch et al., 2024). The near-surface aquifers are composed of Quaternary loose rock deposits (Beer et al., 2016).

2.2. Input data for the mGROWA model

2.2.1. Historical period

The elevation profile of Schleswig-Holstein is shown in Fig. 1a (LVermGeo SH, 2009). Elevations in the western marshlands are extremely low, while some small hills (maximum elevation of 168 m a.s.l.) are present in the east of the state. 26 % of the study area is less than 5 m above sea level.

The land cover (Fig. 1b) is taken from a combined "Integrated Administration and Control System" (German: "Integriertes Verwaltungs- und Kontrollsystem"; InVeKoS) and cadastre information system (German: "*Amtliches Liegenschaftskatasterinformationssystem*"; ALKIS) dataset prepared by Tetzlaff et al. (2024). Almost half of the state is covered by cropland (48 %), with permanent grassland (26 %) the second most common land cover and forests (consisting of deciduous forest, coniferous forest and mixed forest) the third most at 11 %. The percentage of surfaces that are sealed (i.e., impervious) is shown in Fig. 1c, with concentrated regions of high sealing in the urban areas such as Kiel, Lübeck and Flensburg.

To define soil profiles for all modelled raster cells, horizon-specific information was taken from the "Bodenübersichtskarte" (Soil Overview Map), with a scale of 1:250,000 (LLUR, 2017). Fig. 1d shows the mean field capacity over the modelled depth of 2.10 m, which is highly correlated with the soil types. A central band running from the northwest to the south (geest) is dominated by gleyic soils and podzols, which have the lowest field capacity values (mostly < 25 %). The eastern uplands comprise of pseudogleys, luvisols, cambisols and fens, which have field capacity values ranging mostly from 25 % to 45 %. The marshland soils along the west coast have the highest field capacity values, mostly over 35 %.

Three input data layers were adopted from Tetzlaff and Kuhr (2011), and these are shown on Figs. 1e to 1g. The first is the spatial distribution and depth categories for surface-near groundwater (Fig. 1e), which was derived using morphological, soil moisture and land cover information. 37.4 % of the land area in the state exhibits near-surface groundwater, noting that a lower groundwater level category number denotes groundwater nearer to the surface. As groundwater depth varies throughout the year, these categories are converted into monthly depths according to the relationships presented in Engel et al. (2012) and Bug et al. (2020). Soils that exhibit waterlogging properties are shown on Fig. 1f, where the higher the category, the stronger the soil waterlogging tendencies. To derive the areas that are artificially drained (Fig. 1g), Tetzlaff and Kuhr (2011) combined geofactors such as soil parameters, land use type and relief characteristics. There are very high levels of drainage throughout the state, corresponding to approximately 55 % of the land area.

Thick till layers extend throughout large areas of Schleswig-Holstein (Fig. 1h), which are thickest in the eastern uplands (Van der Wateren, 1999; Kunkel and Wendland, 2020). The inhomogeneous structure of these till layers is a result of subglacial processes, including lodgement bed deformation, ploughing and melt out (Benn and Evans, 2010). The presence of these layers can reduce groundwater recharge rates, hence they are considered as part of the adjusted runoff separation mechanism for Schleswig-Holstein (see

Section 3.1).

Precipitation and annual potential evapotranspiration gridded datasets at a spatial resolution of 1 km for 1971–2020 are provided by the DWD and are derived through spatial interpolation techniques based on point-based data at weather stations (DWD, 2018, 2020). Shown on Fig. 2 are the mean annual values of these variables for 1971–2000. This is the reference period we used for this study, because it is the last 30-year period with the last year ending in a zero, before the RCP forcings in the CMIP5 climate projections take effect in 2006 (see Section 3.4). The mean annual precipitation over this period is 786 mm/yr, with the values generally increasing from the east of Schleswig-Holstein to the west. In addition to this east-west gradient, there is also a weak correlation between precipitation increasing with elevation (see Fig. 1a). The mean annual potential evapotranspiration for 1971–2000 is 543 mm/yr, with the highest values in the east of the state. Compared to the values of annual precipitation, the absolute range in values for annual potential evapotranspiration is substantially lower.

For the calibration and validation of the mGROWA model for Schleswig-Holstein, daily discharge data from 145 gauging stations were provided. After the removal of stations where: i) less than 10 years of discharge data were available; ii) the time series exhibited gaps greater than one month; iii) catchment delineation was unclear; and iv) catchments exhibited substantial anthropogenic influences, 112 stations remained for the validation and calibration.

2.2.2. Climate projections

For climate change impact assessment studies in Germany, the DWD recommends the use of its “Reference Ensemble v2018”, which includes climate models from the EURO-CORDEX (Jacob et al., 2014) and ReKliEs-De (Huebener et al., 2017) initiatives, and at the time of this study contains 44 individual RCMs (DWD, 2023). The climate models in this ensemble are from the Coupled Model Intercomparison Project Phase 5 (CMIP5), which have altered radiative forcings according to RCP starting in 2006 (Taylor et al., 2012). Although more updated GCMs from CMIP6 are available, which have altered radiative forcings starting in 2016, the process of generating RCMs and of the DWD selecting an ensemble for application for Germany is not complete at the time of publishing this manuscript. Therefore, the climate ensemble based on CMIP5 projections is used, which consists of 11 RCP2.6 members, 12 RCP4.5 members and 21 RCP8.5 members in the EUR11 (0.11°) grid. Daily data from 1971–2000 at the nodes for each climate model were downloaded from the portal of the German Climate Computing Centre. The GCMs and RCMs used for each ensemble member are listed in the Supplemental Material.

2.3. Evaluation areas over Schleswig-Holstein

Water resources management decisions are made at varying spatial scales. For this study, the simulated changes in groundwater recharge were evaluated using three existing datasets for spatial aggregation, which are shown in Fig. 3. The 27 hydrogeological subregions in Schleswig-Holstein (Fig. 3a) belong to six hydrogeological regions (Beer et al., 2016). Marshlands dominate the western coast along with geest islands, a central band from northwest towards the south is dominated by old moraine deposits (high geest),

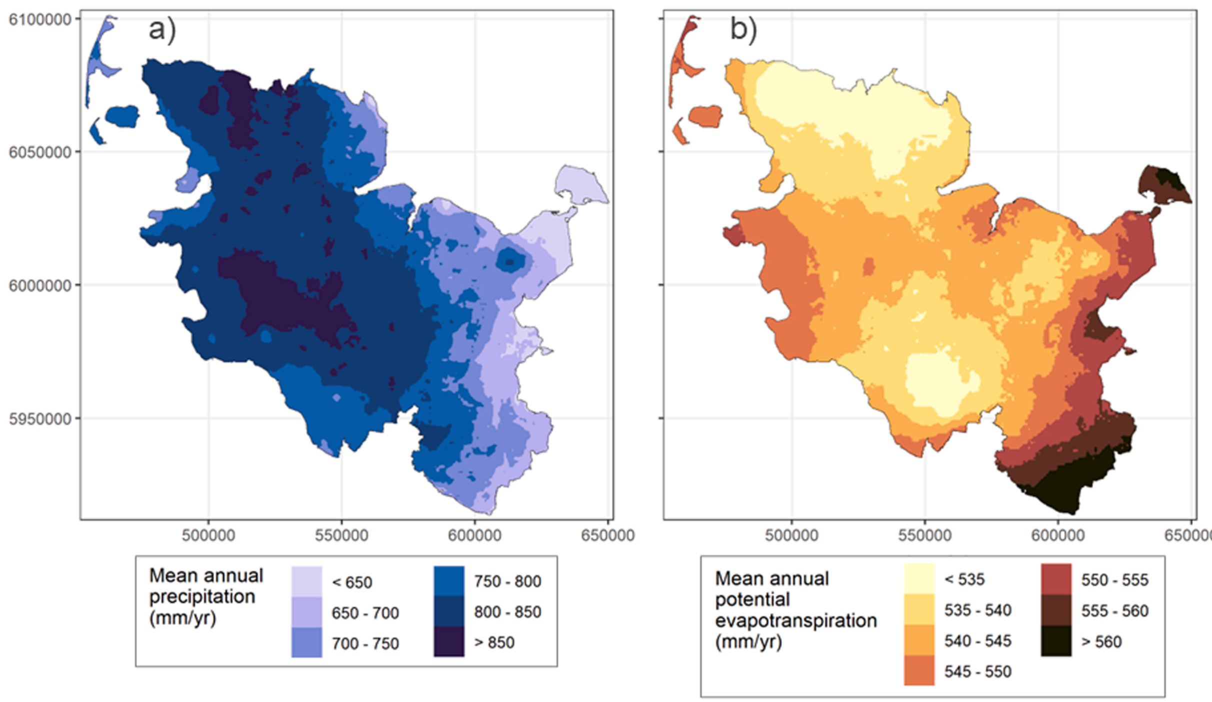

Fig. 2. Mean annual a) precipitation; and b) potential evapotranspiration for 1971–2000.

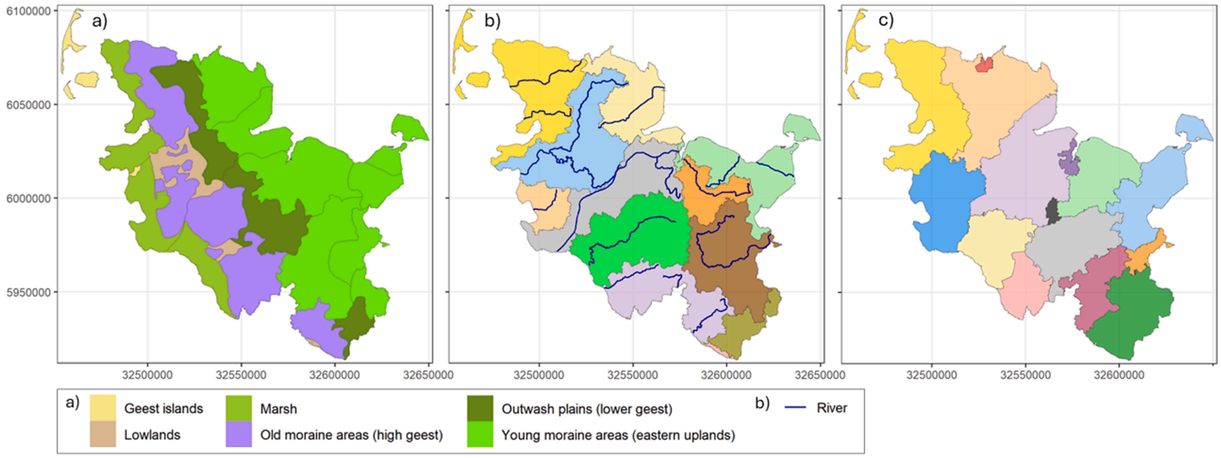

Fig. 3. Evaluation areas over Schleswig-Holstein: a) hydrogeological regions (Beer et al., 2016); b) planning units (LAWA, 2013); and c) administrative areas.

lowlands and outwash plains (lower geest), and the eastern uplands are dominated by moraine (till).

The 13 planning units (Fig. 3b) according to the European Union Water Framework Directive (EU-WFD, 2000) are based on surface catchment areas, with the major rivers also shown in the figure. The 15 administrative areas of Schleswig-Holstein, corresponding to the district level, are shown on Fig. 3c. As both the hydrogeological regions and planning units are based on geophysical characteristics, some areas extend beyond Schleswig-Holstein; however, only the areas within the state are evaluated here.

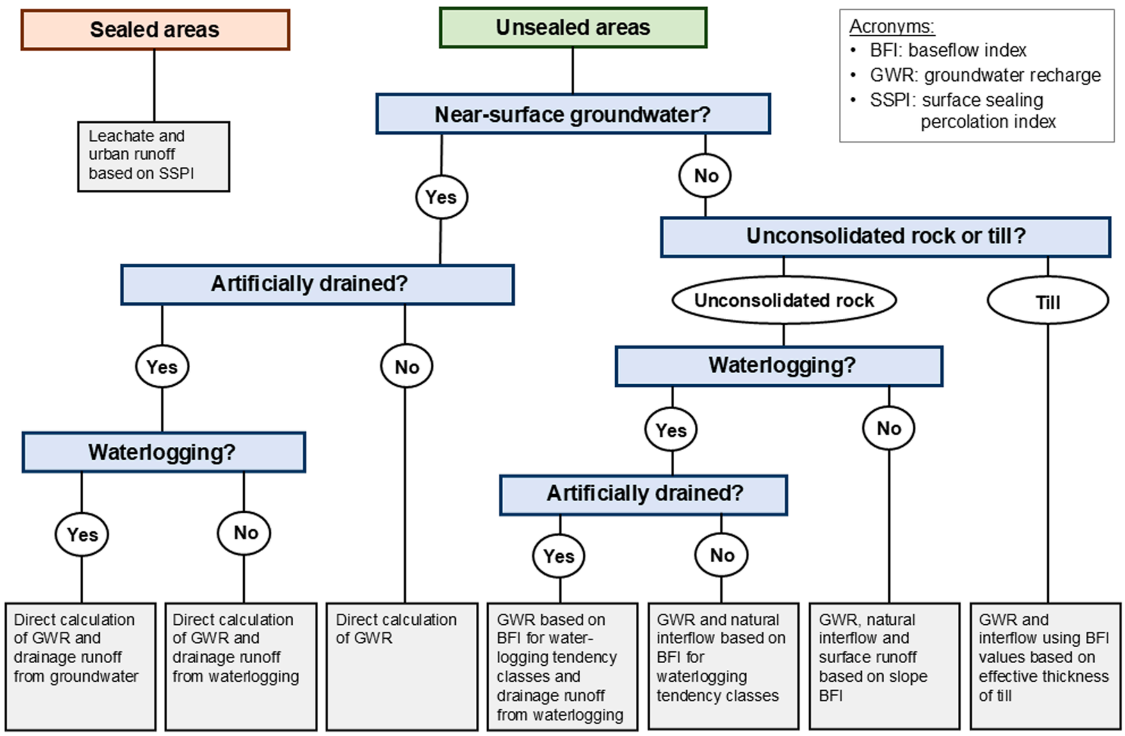

Fig. 4. mGROWA runoff separation decision tree, modified for the case study of Schleswig-Holstein. Separation of total runoff is completed for each modelled raster cell. The option for till layers shows the modification from the standard mGROWA model. Adapted from Herrmann et al. (2015) and Wolters et al. (2023).

3. Methods

3.1. The mGROWA model

mGROWA is a one-dimensional, deterministic hydrological model that represents the water balance over multiple soil layers at a high spatio-temporal resolution. The model consists of two parts: i) daily calculation of actual evapotranspiration, water distribution across the soil layers and total runoff; and ii) separation of the total runoff into its components at the monthly temporal scale (Herrmann et al., 2013, 2015).

The high spatial resolution of the mGROWA allows for high spatial heterogeneity in the input datasets (topography, land use, soil properties, etc.; see Fig. 1) to be well represented in the hydrological modelling (Pisinaras et al., 2023). A summary of the inputs, processes and outputs of the first part of the mGROWA model can be found in Wolters et al. (2023; their Fig. 2). The daily actual evapotranspiration is calculated using land use-specific crop coefficients (k_c factors) that can vary according to month, with consideration given to the water available over the effective root depth and application of the Disse function (Disse, 1995). The model operates as a bucket-style model (allowing also for preferential flow and for water to be transpired simultaneously from multiple soil layers), and the total daily runoff is considered to be the sum of the surface runoff and the water leaving the bottom soil layer modelled (Wolters et al., 2023).

As over a third of the land area in Schleswig-Holstein exhibits near-surface groundwater (see Fig. 1e), and much of this is artificially drained (see Fig. 1g), how the mGROWA model characterises the hydrological processes over these areas is of high relevance for this study. For raster cells with near-surface groundwater, the depth of the water table is a monthly varying input, with the depths assigned based on the values listed in Bug et al. (2020). For groundwater-influenced raster cells with artificial drainage, in months where the naturally occurring water table would be higher than the depth of drainage, the water table is lowered to the depth of the drainage (Herrmann and Wendland, 2021b; their Fig. 4). The water table represents a source of water available for transpiration, either directly if the root depth extends into the groundwater table, or due capillary rise processes, which are modelled based on rates reported according to soil type (Renger et al., 2009; Müller and Waldeck, 2011).

A decision tree (Fig. 4) is used to define runoff separation, whereby for each raster cell, a hierarchical process is used to define the portions of total runoff assigned as direct runoff (consisting of surface runoff, direct runoff from urban areas, natural interflow, and drainage runoff) and as groundwater recharge. Note that for artificially drained groundwater-influenced areas, whether the runoff is modelled as drainage runoff or groundwater recharge depends on the groundwater level in the particular month. Some branches of the decision tree employ baseflow indices (BFIs), which quantify the fraction of total runoff that is assigned as groundwater recharge, with the remainder assigned as natural interflow (Haberlandt et al., 2001; Bloomfield et al., 2009). Underlying this concept is the assumption that over areas with comparable site characteristics, the long-term fraction of total runoff that contributes to groundwater recharge can be regarded as constant. For this study, the assumption was made that the processes of groundwater recharge in areas with thick till layers (Fig. 1h) is similar to that of bedrock, for which this BFI concept is typically used in mGROWA (Stein et al., 2024). The farthest right branch of the decision tree in Fig. 4 showing the implementation of BFI values for till represents an alteration to the typical decision tree used for runoff separation in mGROWA (Herrmann et al., 2015; Wolters et al., 2023).

The mGROWA model can be calibrated against observed discharge values in an iterative process where parameters (e.g., BFI values for till layers) are adjusted to improve the model performance, ensuring that values remain within plausible parameter ranges reported in literature. The need for calibration for parameters such as land-use specific k_c factors is minimal, as there is extensive literature with estimates of these values (e.g., Allen et al., 1998; ATV-DVWK, 2002; Dietrich et al., 2021) and the parameterisation of the mGROWA model should not deviate significantly from such established parameters.

The groundwater recharge simulated by mGROWA is the downward water simulated using the bucket-style model minus the water extracted by vegetation from near-surface groundwater in the form of capillary rise or direct transpiration when the root zone extends into the water table (Wolters et al., 2023). Over some areas, this extracted water can exceed the total downward-flowing water, meaning that over the course of a year, an area can be considered a groundwater depletion zone. Also note that in mGROWA, groundwater recharge is not calculated over water bodies.

For detailed descriptions of the mGROWA model, the reader is referred to Herrmann et al. (2015) and Wolters et al. (2023).

3.2. Model setup for Schleswig-Holstein

For this work, we set up the mGROWA model with a raster grid size of 100 m, meaning that approximately 1.56 million individual raster cells were modelled over Schleswig-Holstein. Each 100 m grid-cell was modelled with seven soil layers, each 30 cm deep. The historical model was run for the hydrological years 1971–2020, with the hydrological year in Germany running from November to October.

A total of 112 discharge stations with daily data over the period 1981–2020 satisfied the criteria for use in the evaluation of the model performance for estimating total runoff generated (length of record greater than 10 years, minimal data gaps, clearly delineated catchment, minimal area of catchment extending outside of the state, and discharge data that passed a plausibility assessment). The catchment areas corresponding to each station are adopted from Tetzlaff et al. (2017). As the mGROWA model considers neither the temporal aspect of flow routing nor transit time in aquifers, total runoff assessments are made using multiannual means of flow generation over catchments, under the assumption that long-term changes in storage can be considered negligible (Wolters et al., 2023; Stein et al., 2024). For each catchment, the mean annual total flow simulated by mGROWA over the period for which discharge data were available were compared against the observed flow, and the Nash-Sutcliffe Efficiency (NSE; Nash and Sutcliffe, 1970) and the

Kling-Gupta Efficiency (KGE; Kling et al., 2012) were calculated considering all evaluated catchments simultaneously, as per Wolters et al. (2023).

For the evaluation of the groundwater recharge output, the assumption was made that the long-term groundwater recharge is equivalent to the baseflow component of the streamflow (Healy, 2010; Schilling et al., 2021). Over unconsolidated rock areas in Germany, the method from Wundt (1958) is commonly used for baseflow separation, while the method from Demuth (1993) is often applied for areas with bedrock (Herrmann et al., 2015). To maintain consistency with the modelling assumption that areas with thick till layers (Fig. 1h) can be modelled using the same BFI concept typically used for bedrock areas, the method from Demuth (1993) was used for baseflow derivation for catchments dominated by till (i.e., $>$ 50 % coverage; 73 of the 112 catchments) and the Wundt method for catchments dominated by unconsolidated rock (39 catchments).

Discharge stations with negative values in the time series (e.g., due to tidal influences) and those that did not meet the conditions specified by Demuth (1993) were excluded from the analysis. As a result, the number of catchments considered for model evaluation of the groundwater recharge component was reduced to 78. As before, the NSE and KGE were calculated considering all catchments at once, comparing the long-term means of baseflow derived from the hydrographs against the modelled groundwater recharge over the temporal period for which each discharge station had continuous data. Note that grid-cells modelled as groundwater depletion areas were still included with their negative values in the calculation of the spatial mean groundwater recharge over each respective catchment.

3.3. Preparation of climate model data

Climate models exhibit biases in their results, particularly in the representation of the complex spatial and temporal precipitation patterns (Copernicus Climate Change Service, 2021). We applied the “Local Intensity Scaling” method (LOCI; Schmidli et al., 2006) to correct the daily precipitation at each node point for each climate model. This method applies a precipitation intensity threshold so that the precipitation quantities and number of days with precipitation matches that of the observed data over the historical period (1971–2000, see Section 2.2.1).

The LOCI method is implemented in two steps: first, a threshold value for the wet days is determined for each month from the daily precipitation time series of the climate model, so that the exceedance of the threshold value corresponds to the frequency of wet days in the observed time series. The scaling factor is then determined based on these wet day intensities (Eq. 1):

$$sc = \frac{\langle p^o : p^o \geq p^o_{WDT} \rangle - p^o_{WDT}}{\langle p^m : p^m \geq p^m_{WDT} \rangle - p^m_{WDT}} \tag{1}$$

where sc is the calculated scaling factor (dimensionless), p^o is the daily observed precipitation (in mm), p^m is the daily precipitation from the climate model (in mm), and WDT is the wet day threshold. The angle brackets denote long-term means. The time series of the climate model is then bias corrected (Eq. 2):

$$\hat{p}(t) = \max\left(p^o_{WDT} + sc\left(p^m(t) - p^m_{WDT}\right), 0\right) \tag{2}$$

Where $\hat{p}$ denotes the corrected precipitation values, and t refers to the day. For each climate model, the LOCI correction was undertaken at each node of the RCM, with the observed dataset extracted from the corresponding grid-cell of the observed precipitation dataset (DWD, 2020). From the derived bias-corrected time series at each node, we implemented a bilinear interpolation to generate the daily precipitation grids for hydrological modelling.

While daily precipitation values are provided by the climate models, this is not the case for the potential evapotranspiration, which is also required as an input for the mGROWA model. A standard method for the derivation of potential evapotranspiration in Germany is shown in Eq. 3 (ATV-DVWK, 2002), which is based on the Penman-Monteith method (Monteith, 1965). This method considers many variables that influence potential evapotranspiration (e.g., temperature, humidity, surface pressure, wind speed and net radiation) and is thus considered a preferred method when these variables are available.

$$et_O = \frac{s}{s + \gamma^*} \bullet Rn^* + \frac{90 \bullet \gamma}{s + \gamma^*} \bullet \frac{e_s(T)}{T_{mean} + 273} \bullet \left(1 - \frac{U}{100}\right) \bullet v_2 \tag{3}$$

where et_O is the potential evapotranspiration (mm/d), T_{mean} is the mean daily air temperature (°C), $e_s(T)$ is the saturation vapour pressure (hPa), s is the slope of the saturation vapour pressure curve over water (hPa/K), γ is the psychrometric constant (hPa/K), γ^* is the modified psychrometric constant (hPa/K; Eq. 4), Rn^* is the water evaporation equivalent of the net radiation (mm/d), U is the relative humidity at a height of 2 m (%), and v_2 is the mean daily wind speed at a height of 2 m (m/s).

$$\gamma^* = \gamma(1 + 0.34 \bullet v_2) \tag{4}$$

For four of the climate models (1 x RCP 2.6 and 3 x RCP 8.5), there are insufficient output variables provided in the climate models to implement the ATV-DVWK (2002) method to derive potential evapotranspiration. For these four climate models, the Hargreaves-Samani method was used, which requires only temperature as input (Hargreaves and Samani, 1985; Eq. 5). These four climate models are identified with footnotes in the Supplemental Material.

$$et_O = 0.0023 \bullet (T_{mean} + 17.8) \bullet (T_{\max} - T_{\min})^{0.5} \bullet R_a \tag{5}$$

where T_{max} is the maximum daily air temperature (°C), T_{min} is the minimum daily air temperature (°C), and R_a is the water evaporation equivalent of the mean daily extraterrestrial radiation (mm/d). As with the precipitation data, we used bilinear interpolation to convert the values of derived potential evapotranspiration at each node to the 100 m model grid used for this study.

The long-term mean annual potential evapotranspiration and precipitation for each climate model were calculated over the two evaluation periods 2041–2070 and 2071–2100. The percentage change between these values and the means of the corresponding climate models over the historical period 1971–2000 are presented on Fig. 5, divided into the three RCPs. As expected, increasing temperatures tend to drive increasing rates of potential evapotranspiration, most pronounced for the RCP8.5 scenario. Most models show an increase in precipitation in future periods, in particular for the period 2071–2100, where all except three climate models (2 x RCP2.6 and 1 x RCP8.5) show an increase. For almost all RCPs over both evaluation periods, the range of the long-term mean percentage change in potential evapotranspiration for all climate models is smaller than the range of the long-term mean percentage change in precipitation.

3.4. Assessment of climate impacts

Under the same model setup as for the observed historical period, the mGROWA model was run for all 44 members of the DWD reference ensemble for the period 1971–2100. Only the climatic inputs were changed, with all other inputs kept the same. For each climate model, the change in groundwater recharge was calculated as the difference between the values over the evaluation period and the reference period of the corresponding model.

As the climate forcings in CMIP5 begin in 2006 (Taylor et al., 2012), the reference period was set as 1971–2000, following the recommendation from the World Meteorological Organization (2017) to use the latest possible 30-year period where the last year ends with a zero. The results were assessed over 30-year periods, namely rolling 30-year means as well as the fixed periods 2041–2070 and 2071–2100.

To assess the suitability of the climate models for simulating future changes in groundwater recharge patterns, an evaluation was undertaken of the mGROWA outputs for each climate model compared against that derived using the observed climatic inputs for 1971–2000. For this purpose, the monthly values of groundwater recharge for each grid-cell over this period were used. As the climate models do not aim to exactly reproduce past weather conditions, but rather mimic long-term climate statistics (USDA, 2024), both time series were ordered from the smallest to the largest values before calculation of the KGE. It is important to note that climate models sharing the same GCM and RCM but differing in RCP (see Supplementary Material) are identical for the period prior to 2006. Therefore, only 21 unique climate models are evaluated over this historical period.

Robustness tests can be used to evaluate the reliability of ensemble projections. We used the two criteria set by Pfeifer et al. (2015)

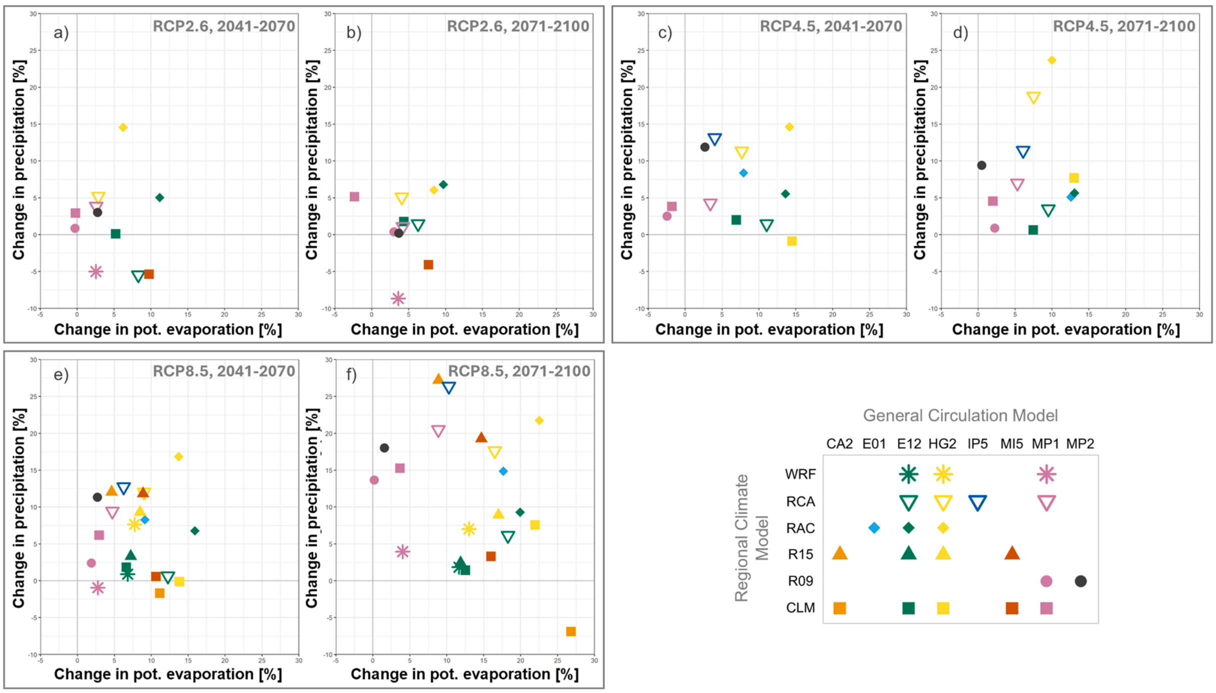

Fig. 5. Mean annual changes in potential evapotranspiration and precipitation compared to the corresponding reference period 1971–2000 for all ensemble members. Figures a) & b) show the 11 RCP2.6 model members for the periods 2041–2070 and 2071–2100. Figures c) & d) show the same for 12 RCP4.5 members, and e) and f) the same for the 21 RCP8.5 members. The codes for the GCMs and RCMs are listed in the Supplementary Material.

to assess the robustness of the results for each RCP:

1) At least 66 % of the climate models must agree in the direction of change; and
2) At least 66 % of the ensemble members must show a significant change in the distribution of annual groundwater recharge values.

The two-tailed nonparametric Mann-Whitney-Wilcoxon U-test was used for this purpose (Wilcoxon, 1945; Mann and Whitney, 1947), using the annual groundwater recharge values for the periods 2041–2070 and 2071–2100 against the reference period (1971–2000) of the corresponding climate model. To test the null hypothesis that no significant change exists between the two periods, two p-values were assessed: 0.05 and 0.15. The p-value of 0.05 is a frequently used threshold in statistical analyses (Greenland et al., 2016), while the less-stringent p-value of 0.15 is based on studies by Pfeifer et al. (2015) and Herrmann et al. (2021a) in the German

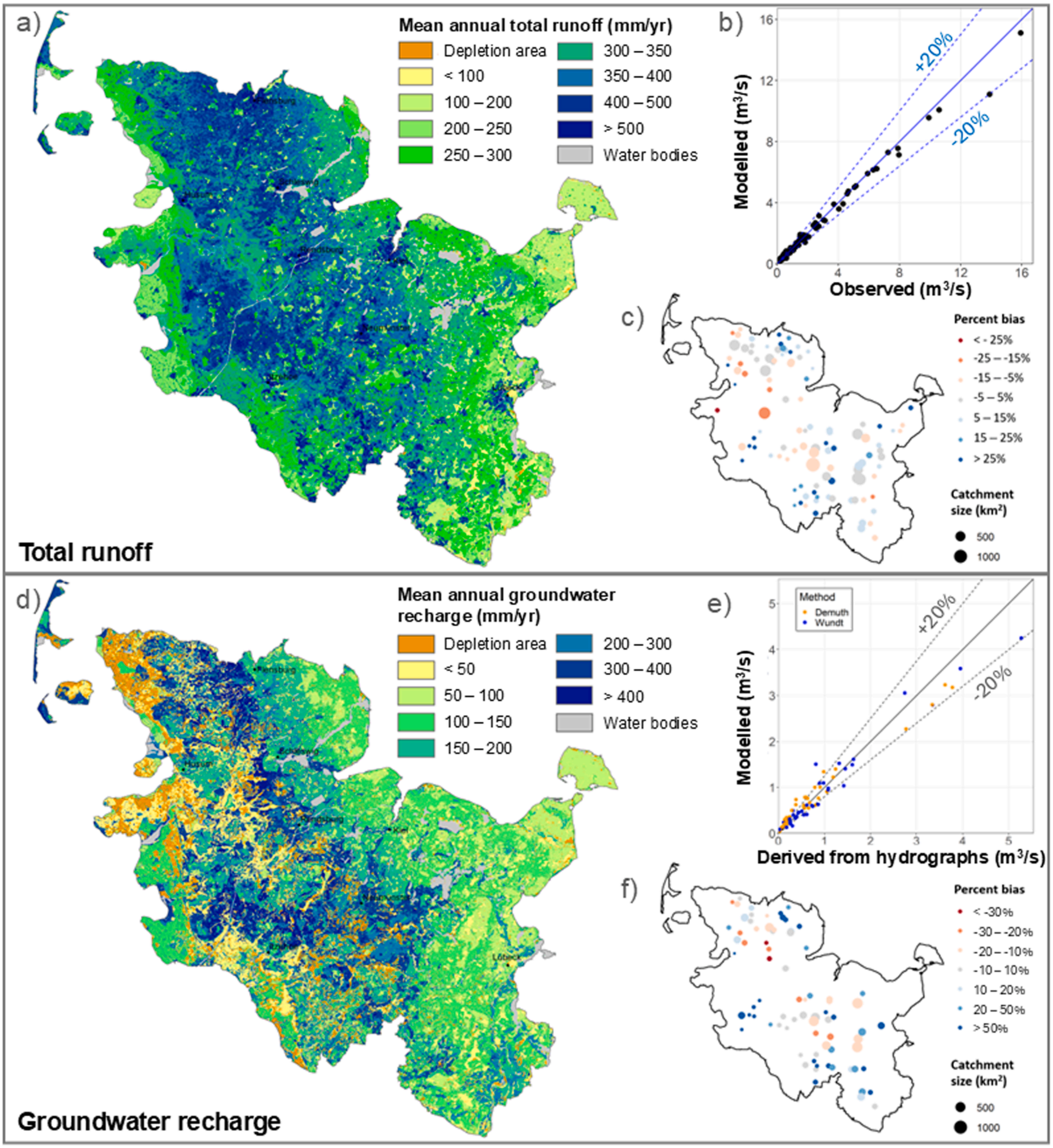

Fig. 6. Evaluation of the mGROWA model for total runoff (a to c) and groundwater recharge (d to f). The maps show the mean annual modelled values for 1971–2000. The scatter plots show the observed values (or values derived from observed hydrographs for groundwater recharge) on the x-axes, and the simulated values from mGROWA on the y-axes. The spatial point plots show the bias value, with the circles plotted at the catchment centroids and their size proportional to the catchment size.

context, and accounts for the fact that nonparametric tests have less power than parametric ones, meaning that results are often less likely to show significant p-values (Politi et al., 2021).

For each of the three RCPs, we also implemented the concept of "climate railguards" proposed by Linke et al. (2024) to quantify the likely changes to groundwater recharge rates in Schleswig-Holstein. This concept considers the range between the 15th and the 85th percentiles of the results to be the likely range of potential changes to the system. The recommendation for using climate railguards comes from the federal and state expert meeting in Germany, with the aim of providing a plausible range of likely developments due to climate change, while removing outliers from results of modelling using climate ensembles. The Q5 algorithm described in Hyndman and Fan (1996) was used to calculate the percentiles.

Lastly, the results from the application of the climate railguards were assessed after aggregation to the three different spatial scales introduced in Section 2.3. This allows regional differences and trends to be extracted from the results to assist in water management planning and allows observation of the impacts of the choice of the spatial aggregation scale.

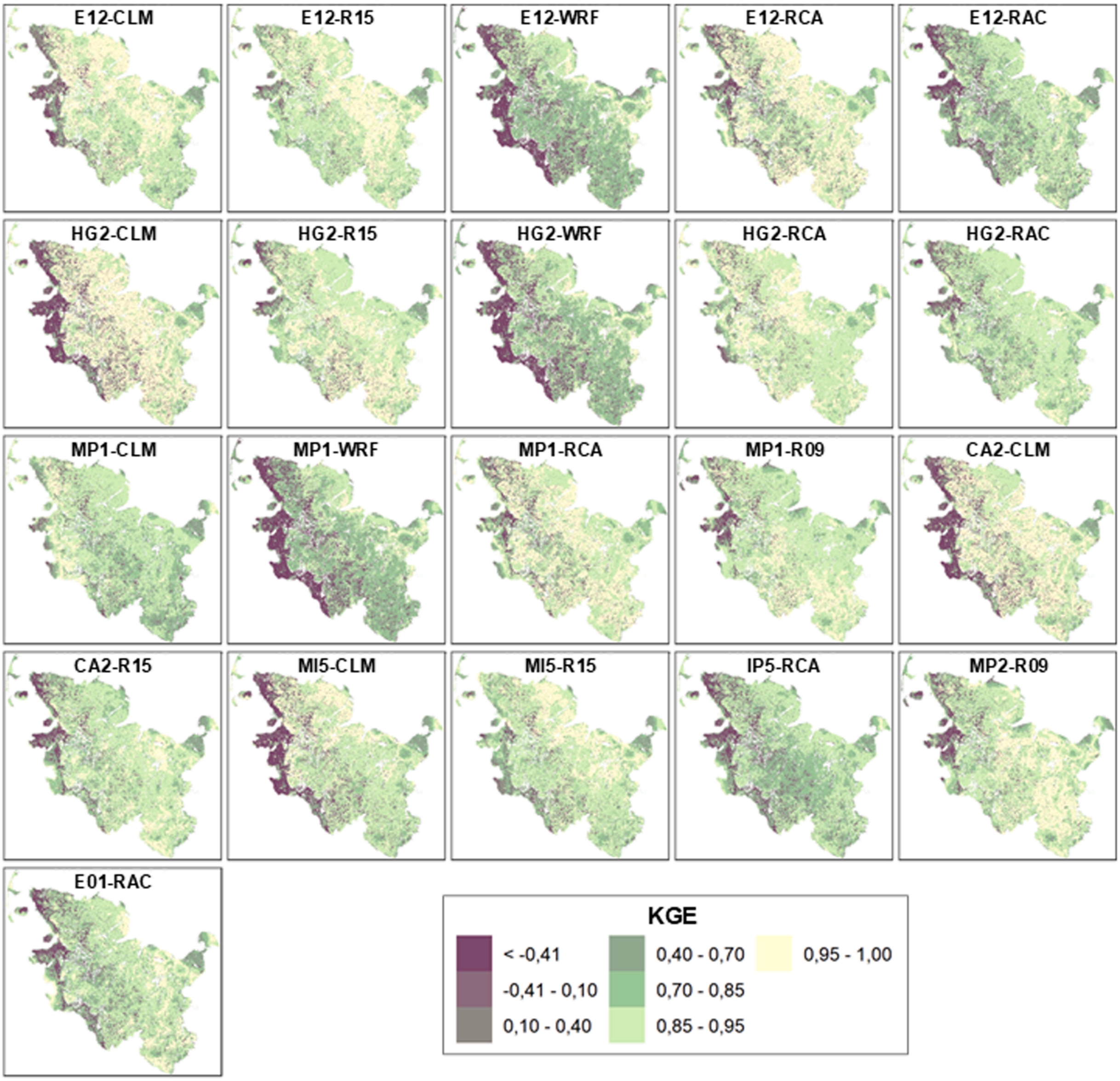

Fig. 7. Monthly KGE values for groundwater recharge for the historical parts of the climate models, calculated for all modelled grid-cells over the period 1971–2000.

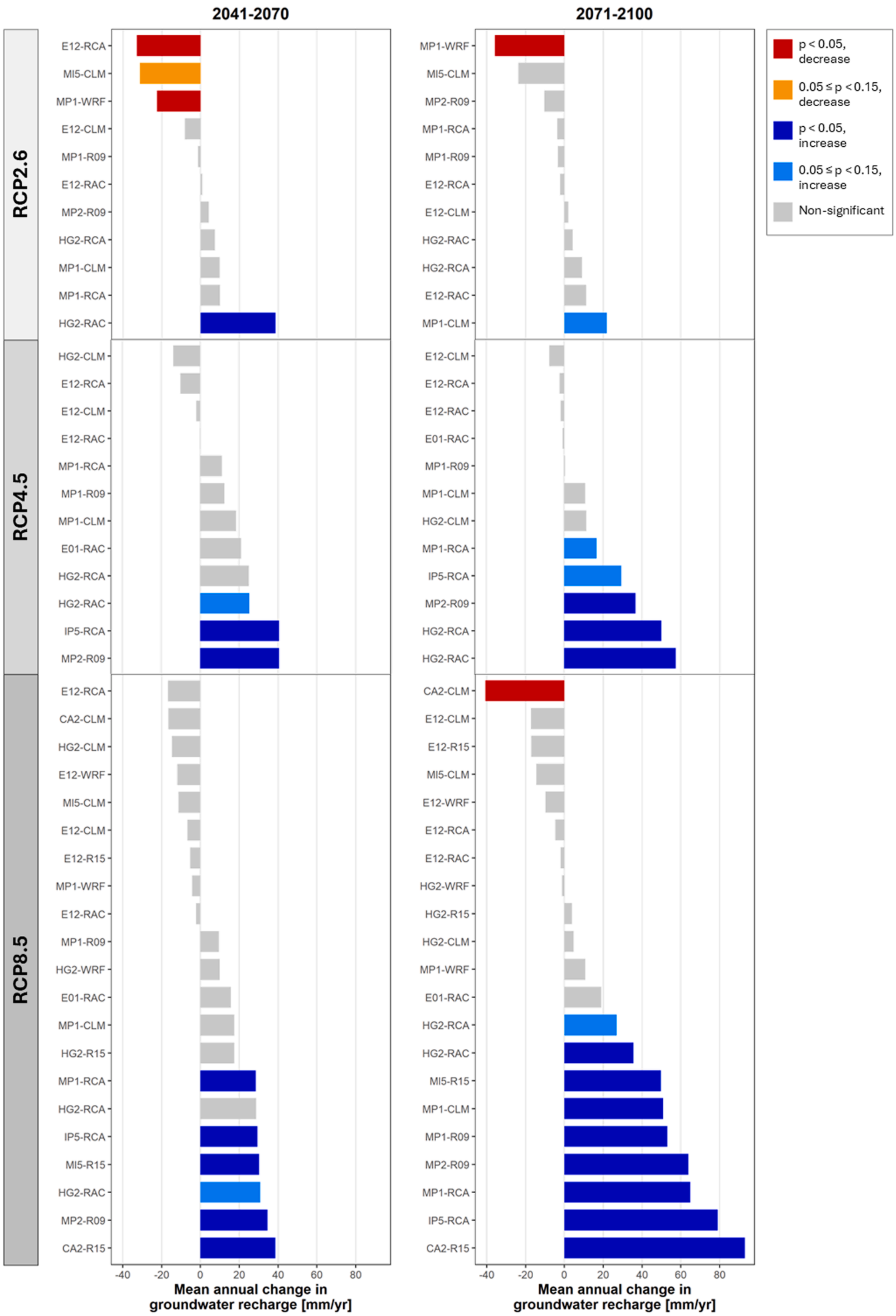

Fig. 8. Spatial mean of annual changes in groundwater recharge and robustness assessment for the 44 climate models for a) 2041–2070 and b) 2071–2100. Significant increases are shown in dark and light blue and significant decreases are shown in red and orange, while grey indicates that a result was non-significant.

3.5. Software used

The mGROWA models were run using *Java*. The *R Project for Statistical Computing* was used for data preparation, results analysis and the generation of output plots, using the packages *terra* (Hijmans et al., 2022), *sf* (Pebesma, 2018) and *ggplot* (Wickham et al., 2016).

4. Results

4.1. Model evaluation

The performance evaluation of the mGROWA model for Schleswig-Holstein based on historical observations is shown on Fig. 6. Firstly, Fig. 6a shows the mean annual simulated total runoff for 1971–2000. The scatter plot in Fig. 6b shows the mean annual modelled total runoff against the mean annual observed total discharge for the 112 evaluated catchments, noting that the evaluation was performed for the period 1981–2020. The NSE is 0.99 and the KGE is 0.94, indicating a very good performance. Fig. 6c shows the spatial performance of each catchment, with blue shades indicating an overestimation of modelled total runoff and red shades an underestimation. This demonstrates that there is no clear spatial trend of overestimation or underestimation of the model.

Similarly, Fig. 6d shows mean annual simulated groundwater recharge for 1971–2000, while Fig. 6e shows the evaluation of the modelled groundwater recharge values for the 78 catchments used for its evaluation, with the colour of the circles indicating the method used for the hydrograph separation procedure (see Section 3.2). Here, the NSE and KGE values are 0.95 and 0.87, respectively, again demonstrating strong model performance. The plot of the spatial performance of the catchments for groundwater recharge modelling (Fig. 6f) again shows no clear spatial trend. This suggests that the till layers have been well represented in the hydrological modelling.

The evaluation of the modelled groundwater recharge for the 21 historical components of the climate models for the period 1971–2000 was performed against values of groundwater recharge derived from the mGROWA model run with observed climatic inputs (see Section 3.4). The results for the KGE at the monthly temporal scale are shown on Fig. 7, with reasonably high KGE values indicating good performance for most models for most areas evaluated. The choice of −0.41 as the threshold value for the colour scale is because below this value, the model performance can be considered as poor (Knoben et al., 2019). Over the marshy areas in the west, where near-surface groundwater bodies and artificial drainage are prevalent (see Fig. 1), there are higher discrepancies between the groundwater recharge based on the historical observations and that of the climate models. This is due to: i) the increased complexity in modelling these interactions; and ii) the lack of catchments over which the model could be calibrated for groundwater recharge (see Fig. 6c).

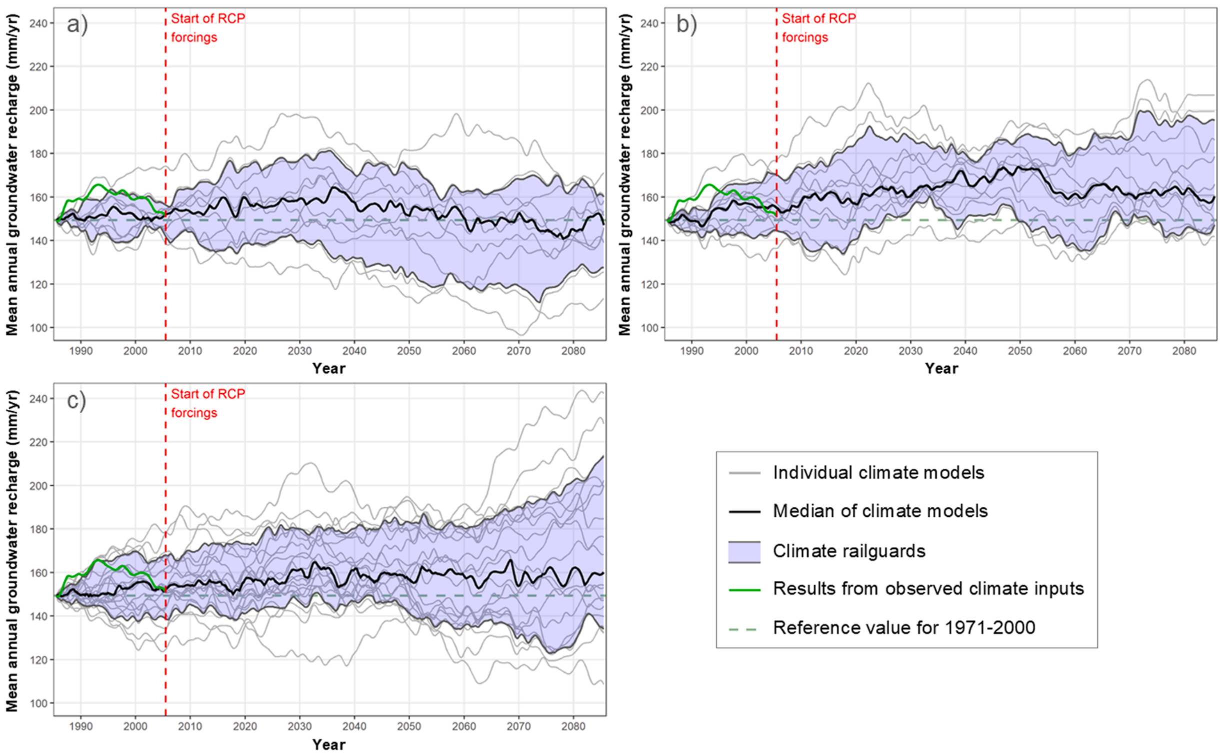

Fig. 9. Application of the climate railguards concept for the a) RCP2.6, b) RCP4.5 and c) RCP8.5 scenarios. All results show the 30-year rolling means of the simulated annual groundwater recharge.

Despite this, the results presented on Fig. 7 still suggest a strong overall agreement, meaning that the mGROWA model set up for Schleswig-Holstein is considered suitable for the assessment of climate change impacts to groundwater recharge using the DWD reference ensemble.

4.2. Climate change impacts on total groundwater recharge

The mean annual changes in groundwater recharge as well as the robustness assessments for 2041–2070 and 2071–2100, calculated over all of Schleswig-Holstein, are shown in Fig. 8. For the RCP2.6 scenarios, 6 of the 11 models show an increase in groundwater recharge for the first evaluation period and 6 of the 11 show a decrease for the second evaluation period. For both the RCP4.5 and RCP8.5 climate models, the majority show an increase over both periods. The mean annual groundwater recharge for the historical period, calculated using the observed climatic inputs, is 150 mm/yr; hence the magnitude of the changes for many of the 44 climate models are not relatively large.

As the results in Fig. 8 are ordered from largest decrease to largest increase, the order in which the climate models are listed changes between the two periods. Both criteria for a robust change in signal (see Section 3.4) are not simultaneously met for any of the RCPs for either evaluation period. This is true when considering either the standard 0.05 p-value or the less stringent 0.15 p-value threshold. This can be interpreted to mean that for none of the RCP scenarios can it be said with certainty that groundwater recharge will increase or decrease in Schleswig-Holstein.

Despite no robust results being achieved for Schleswig-Holstein, we can also implement the concept of the climate railguards to obtain the range of likely changes in groundwater recharge for the state. Each panel on Fig. 9 corresponds to a different RCP, showing the 30-year rolling means from each climate model (light grey), as well as the median value (black line) and the area covered in the climate railguards (blue shaded area). The annual changes calculated from all climate models were added to or subtracted from the simulated mean annual groundwater recharge from 1971–2000 (150 mm) derived from observed data. The green line shows the results from the observed data, also calculated using a 30-year rolling mean. Note that all values are plotted at an x-coordinate in the middle of the 30-year period considered; for example, the value calculated for 2041–2070 is plotted at an x-coordinate of 2055.5.

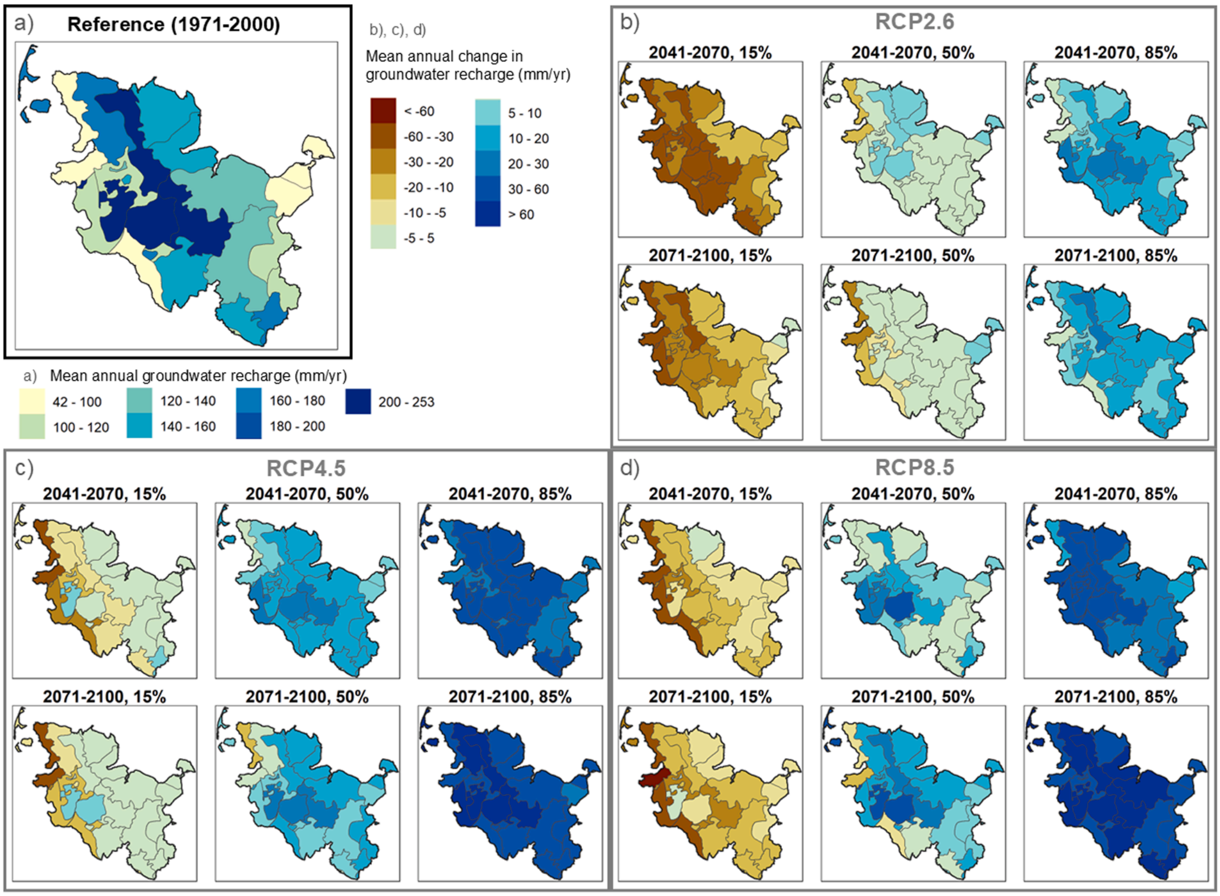

Fig. 10. Mean annual changes in groundwater recharge (2041–2070 and 2071–2100) for the 15th, 50th and 85th percentile for the members of each RCP, aggregated to the 27 hydrogeological regions of Schleswig-Holstein. a) Reference values of groundwater recharge for 1971–2000, simulated using observed climatic inputs; b) to d) the results for each RCP.

It is first important to consider the variations in the 30-year moving average of the observed data (149 mm/yr to 166 mm/yr), which are plotted for a total of 21 30-year periods, as the mGROWA model was run for 50 years of observed climate data (see Section 3.2). This provides some context for understanding the approximate range of natural variability that would be expected from each climate model if precipitation and potential evapotranspiration patterns were not altered due to climate change. The decades with the lowest historical groundwater recharge were 1971–1980 and 2011–2020, which is why the 30-year rolling-mean shown in green is highest around the period that considers the years 1981–2010. The individual climate models exhibit similar interdecadal variability, which becomes less evident when considering only the median and climate guardrails plotted.

The medians shown on Fig. 9 remain above the reference value of 150 mm/yr, with the exception of the RCP2.6 scenario for a short period towards the end of the century. This indicates that most climate models predict an increase in groundwater recharge in Schleswig-Holstein. However, the ranges of the climate guardrails extend both above and below the reference value in most years. The higher the emission scenario, the more the lower and upper limits of these guardrails deviate from each other over the course of the century; this is to be expected given the higher dispersion in the climate inputs seen in the latter evaluation period (Fig. 5).

The groundwater recharge results were aggregated from the 100 m raster to the 27 hydrogeological regions of Schleswig-Holstein (see Fig. 3a). The medians and climate railguards were calculated separately for each hydrogeological area, with the results shown on Fig. 10 for 2041–2070 and 2071–2100. Fig. 10a shows the observed spatial annual means over the reference period, while Fig. 10b to Fig. 10d show the changes relative to the reference level for each RCP. Because these figures show total changes, it is to be expected that the magnitudes of the changes are in general higher in regions where the reference values are also higher.

In the RCP2.6 scenario, the decreases shown in the 15th percentile are more concentrated around the regions with groundwater influence (see Fig. 1e), while the largest increases in the 85th percentile are in the areas that have neither near-surface groundwater nor till layers (see Fig. 1e and Fig. 1h). Individual maps exhibiting both increasing and decreasing groundwater recharge according to hydrogeological area can be seen in the RCP4.5 scenario for 2071–2100. The RCP4.5 climate models generally show both higher and precipitation and higher potential evapotranspiration compared to the RCP2.6 ones (see Fig. 5). This means that there is an even

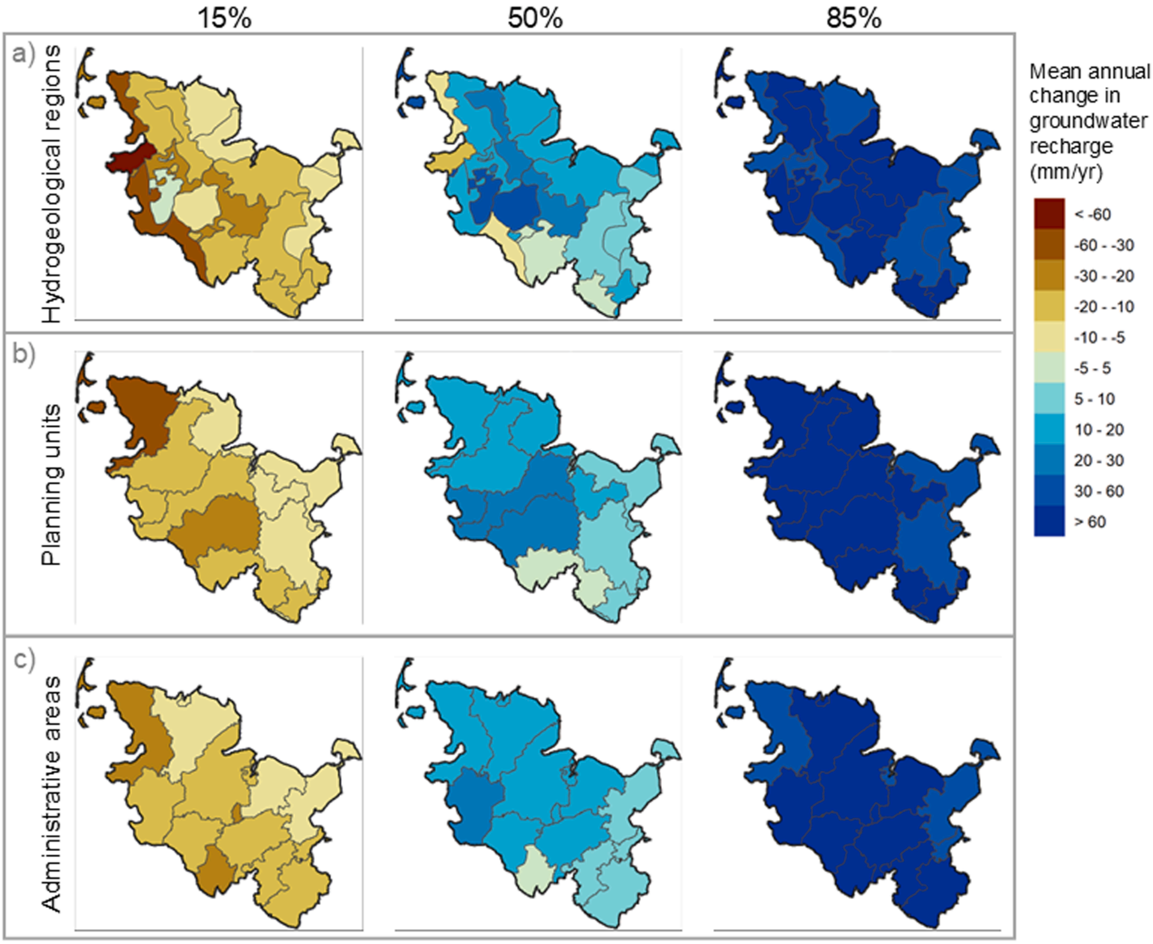

Fig. 11. Mean annual changes of groundwater recharge for 2071–2100 for the 15th, 50th and 85th percentile for the 21 members of the RCP8.5 scenario. The results are aggregated to: a) the 27 hydrogeological regions; b) the 13 planning units; and c) the 15 administrative areas in Schleswig-Holstein.

stronger variability in regions where increased precipitation drives increased recharge, and regions with near-surface groundwater where the increased evapotranspiration drives reduced recharge. For the RCP8.5 scenario, the median also shows high variability, which is more pronounced in the second evaluation period. At the 15th percentile, the pattern of larger decreases in groundwater recharge in the west during the latter 30-year evaluation period becomes very clear. However, the 85th percentile shows a more even increase in groundwater recharge.

The analyses based on aggregations to the planning units and the administrative areas are presented in the Discussion.

5. Discussion

5.1. On estimates of groundwater recharge under climate change

Using the mGROWA model for the case study of Schleswig-Holstein, we were able to assess the expected impacts of climate change for the full reference ensemble recommended for Germany. The high spatial and temporal resolution of the mGROWA model enables the complex system to be adequately captured in the hydrological modelling, notably the land use and soil heterogeneity, prevalent near-surface groundwater, artificial drainage and thick till layers. Although the majority of the climate models predict an increase in future groundwater recharge rates in Schleswig-Holstein, these changes are not considered to be robust, meaning that it cannot be stated with confidence whether groundwater recharge will increase or decrease under any of the RCP scenarios. The results suggest that the effects of increasing potential evapotranspiration (due to increasing temperature) and increasing precipitation (see Fig. 5) cancel each other out to an extent. Furthermore, the increased dispersion in climatic inputs for the RCP8.5 according to different climate models leads to a greater range in modelled results under this scenario.

Our results are consistent with results that suggest that Germany is located in the area within Europe where the changes in groundwater recharge rates are relatively small, as these rates are expected to transition from negative values in the south to positive values in the north (Hiscock et al., 2011; Kumar et al., 2025). The results are also in line with the studies in other regions of Germany that simulated slight increases in groundwater recharge or no substantial change; these include Herrmann et al. (2017), Jing et al., (2020), Herrmann et al. (2021a) and the scenarios RCP2.6 and RCP4.5 in Wunsch et al. (2022). This suggests that our results align with the majority of the studies listed in Table 1, thus supporting the plausibility of the results.

Contrary to our findings, previous studies by Hattermann et al., 2008 and Neukum and Azzam (2012) predicted a decline in groundwater recharge in other regions of Germany. Additionally, Wunsch et al. (2022) predicted a significant drop in the groundwater table under the RCP8.5 climate scenario for sites in Schleswig-Holstein. However, it is important to note that their study simulated groundwater levels rather than recharge. Direct comparisons between our results and these studies remain challenging due to differences in hydrological models, emission scenarios, climate projections and evaluation methods.

5.2. On the spatial scale of analysis

Spatial means of groundwater recharge rates are typically used for water resources decisions, which is why the selection of areas used for aggregation of modelling results is of high importance. The results presented on Fig. 10 are for the hydrogeological regions within Schleswig-Holstein. Shown on Fig. 11 are the results for only the 21 RCP8.5 climate models for the period 2071–2100, firstly repeated for the hydrogeological regions (Fig. 11a) as well as aggregated to the planning units (Fig. 11b) and administrative areas (Fig. 11c). The choice of aggregation areas plays an important role in the outputs achieved, which is most evident in the panels showing the medians of the results (50th percentile) for each area. As the inputs for the mGROWA model are strongly influenced by the hydrogeological conditions, it is not surprising that the spatial heterogeneity in the results is highest when aggregated to the hydrogeological region compared to the planning units or administrative areas. The choice of aggregation areas should therefore be carefully selected to match the aims of the study and the specific planning and management requirements.

5.3. Consideration of non-climatic input changes

In the mGROWA model, the monthly groundwater level in the soil is set as a boundary condition based on Bug et al. (2020). In the future, longer phases with significantly higher or lower groundwater recharge or high abstraction rates could affect the groundwater depth. Furthermore, a global sea-level rise of between about 30 cm and 1 m is expected by 2100 (Fox-Kemper et al., 2021), with a similar regional sea-level rise expected for Schleswig-Holstein (Grinsted et al., 2015). As a large part of Schleswig-Holstein lies at a very low elevation (see Fig. 1a), this sea-level rise could affect the groundwater level in the coastal regions (Habel et al., 2024).

There are three other inputs in the mGROWA model that might change over the century, although they were modelled as static over the entire climate modelling period. The sealed areas, land cover and artificially drained areas may change as a result of climate change, population growth and economic development. However, any estimate of how exactly these input patterns would change involves a very high degree of uncertainty. One advantage of keeping these input patterns static for the entire modelling period is that the effects of changes in climatic inputs can be assessed independently of all other influences.

6. Conclusion

We implemented the mGROWA hydrological model to simulate the changes in groundwater recharge in Schleswig-Holstein until the end of the 21st century for the 44-member full climate ensemble recommended for Germany by the DWD. For the RCP2.6 scenario, the expected changes are minimal, while for the RCP4.5 and RCP8.5 scenarios, the majority of the climate models predict an increase in groundwater recharge for Schleswig-Holstein. However, the robustness assessment found that the changes in groundwater recharge could not be classified as significant for any of the RCPs analysed, meaning that it cannot be stated with confidence as to whether groundwater recharge rates will increase or decrease. The results are consistent with other studies of groundwater recharge under climate change in the region, whereby models tend to predict a small increase, but the changes are not considered robust. We also implemented the climate railguards concept, which considers the range between the 15th to the 85th percentile of results, to determine the likely changes in groundwater recharge for each of the RCP scenarios.

Results of high spatial resolution hydrological models can be aggregated at different spatial scales to provide information that are useful for water management planning. We demonstrated the high importance in selecting the aggregation areas so that they are congruous with the water resources management aims. While the results presented here represent what is currently the most up to date assessment for Schleswig-Holstein, we recommend that a similar study is conducted once the reference ensemble for Germany based on the CMIP6 projections is complete.

CRediT authorship contribution statement

Ian McNamara: Writing – review & editing, Writing – original draft, Validation, Software, Project administration, Methodology, Formal analysis, Conceptualization. **Tim Wolters:** Writing – review & editing, Validation, Methodology. **Bernd König:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Anna-Lena Rugen:** Writing – review & editing, Project administration, Methodology. **Miriam Toro:** Project administration, Methodology. **Martina Flörke:** Writing – review & editing. **Frank Wendland:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Funding

The investigation was funded by the German state of Schleswig-Holstein.

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.

Acknowledgements

This research was supported by the Department of Geology and Soil of the State Office for the Environment Schleswig-Holstein as Geological Survey Schleswig-Holstein. We would also like to thank the three anonymous reviewers for their constructive comments, which have helped to improve the quality of the manuscript.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2025.102507.

Data availability

Data will be made available on request.

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