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Estimates of irrigation requirements throughout Germany under varying climatic conditions

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ABSTRACT

As climate change brings about hotter and often drier summers, an improved understanding of how irrigation requirements vary according to climatic conditions is of increasing importance. Within Germany, temperate conditions have historically enabled most agriculture to be supplied solely by green water, but recent crop yield reductions and crop failures have demonstrated its increased vulnerability to climatic conditions. The raster-based mGROWA hydrological water balance model was implemented over all agricultural areas in Germany for the period 1961–2020 at a high spatial (200 m) and temporal (daily) resolution. Grid-cells were each assigned one of 10 major crop classes, which account for 86.7 % of all agricultural areas in Germany, and effectively all irrigated areas. Using crop-specific irrigation rules that reflect actual practices, irrigation requirements were simulated for all crop areas. To investigate the relationship between climatic water balance over the crop growing season and irrigation requirements, the simulated annual irrigation requirements were compared with the standardised precipitation-evapotranspiration index (SPEI-6), calculated at the end of September. Through this comparison, irrigation requirements could be characterised for near-normal and dry conditions, and results were aggregated to the district level. Additionally, using district-level data on the areas with irrigation infrastructure, the actual water used for irrigation was estimated. The results highlight marked increases in irrigation requirements in dry conditions compared to near-normal conditions (median increase of 72 %), which are more pronounced over crops in silty soils than in sandy soils. The results also demonstrate how the increased irrigation requirements in dry years are in many cases higher than what is suggested by guidelines for irrigation management in Germany. This study provides important information for actors related to the agricultural sector and water management and is based on a robust and transferable framework to quantify how irrigation requirements vary according to climatic variability and local soil conditions.

1. Introduction

Globally, irrigation accounts for approximately 90 % of consumptive water use (McDermid et al., 2023), with climate change expected to be a major contributing factor to future increases in demands (Huang et al., 2019; Rosa, 2022). Within Germany, water extractions for irrigation have historically been relatively small (Siebert and Döll, 2010), as the temperate to cold climate has allowed over 90 % of total crop water consumption in the country to be supplied by green water (Rost et al., 2008), which is the precipitation (P) that remains in the soil and is available to plants. However, the widespread decrease in crop yields and failures during dry years, such as those caused by the European summer droughts of 2003 and 2018 (De Bono et al., 2004; Zink et al., 2016; Beillouin et al., 2020; Conradt et al., 2023), demonstrate the increased vulnerability of agriculture to climate and underscore the importance of irrigation in dry years. In recent dry periods, water conflicts have been reported in some regions of Germany (Kruse, 2018; Riedel et al., 2021; LAWA, 2022). With summer droughts in Germany expected to intensify due to climate change (Grillakis, 2019; Christidis and Stott, 2021), it is imperative to improve our understanding of how climatic conditions drive irrigation requirements in order to be better prepared to meet these future challenges (Engel et al., 2017; Cammalleri et al., 2021).

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Within Germany, irrigation requirements are generally higher in the northern and eastern regions where light sandy soils have a relatively low water retention capacity, meaning that crops can quickly experience water stress in periods of *P* deficits (Drastig et al., 2016; Herrmann et al., 2016). Although less than 10 % of agricultural areas in Germany are equipped with irrigation infrastructure, the area has almost doubled over the last two decades (Fricke and Heidorn, 2004; Destatis, 2021b), and this trend is expected to continue or increase pace (Engel et al., 2017). Water extraction limits for agricultural use exist throughout Germany (Riediger et al., 2016; Teiser, 2019; Ostermann, 2022), and while detailed crop and soil-specific guidelines exist for suggested ranges of water extraction allowances according to normal and dry years (DWA, 2019), there is no consistent approach between districts in determining limits. Although water resource stress from irrigation requirements is growing in certain regions, comprehensive nationwide data on irrigated areas and actual water usage are sporadic, only available for specific years, and are available only at the district or state level. This lack of data availability hinders attempts to quantify irrigation requirements at high spatial and temporal resolutions.

Many studies have incorporated user-defined rules for irrigation application to estimate crop water requirements in Germany at a high temporal scale through the implementation of crop models (e.g., Heidt, 2009; Steidl et al., 2015; Drastig et al., 2016; Herrmann et al., 2016; Maier and Dietrich, 2016; Riediger et al., 2016; Bernhardt et al., 2022). Most of these studies are regional, with only the study from Drastig et al. (2016) covering all of Germany. Their study calculates requirements for only four crop types, modelled at a much coarser resolution than the farm scale. To the best of the authors' knowledge, there are no comprehensive analyses of water requirements for the majority of common crops over all of Germany at a high spatial resolution. Furthermore, the studies listed do not differentiate between the irrigation requirements for crop areas that are actually equipped for irrigation and those that are not. A summary of these studies over Germany, with the study area, period modelled, crops, model used and irrigation rules is included in the Supplement (Table S1).

As irrigation requirements are highly dependant on the prevailing meteorological conditions, a comprehensive assessment of the interannual variability of requirements should be based on a relatively long time series (Döll and Siebert, 2002). To characterise the relationship between meteorological drought and agricultural drought, various studies have compared the standardised precipitation-evapotranspiration index (SPEI; Vicente-Serrano et al., 2010; Beguería et al., 2014) with information related to agricultural droughts (e.g., Bachmair et al., 2018; Parsons et al., 2019; Vicente-Serrano et al., 2019; Das et al., 2022; Qin et al., 2023). As meteorological data are readily available, the linking of irrigation requirements to meteorological drought conditions can serve an important need for water resource planning for both researchers and practitioners.

This research sets out to determine irrigation requirements in Germany in both near-normal years and dry years, as defined by the SPEI meteorological drought index. This was achieved through the implementation of the process-based mGROWA hydrological water balance model (Herrmann et al., 2013) at a high spatial and temporal resolution (200 m, daily) over all agricultural areas in Germany for the 60-year period 1961–2020.

2. Materials and methods

2.1. Study area and data

Germany is divided into 16 federal states, which can be divided further into the district level (*German: Kreise*). Under the Nomenclature of territorial units for statistics (NUTS) hierarchical classification system, the state level is the "NUTS-2″ level, while the district level is the "NUTS-3″ level. As many water management decisions are made at this district level (Hohenwallner et al., 2011; BMUV, 2023), the statistics presented in this study have been aggregated to it. Fig. 1 illustrates the study area of Germany, showing the spatial patterns of important input variables for the estimation of irrigation requirements. Shown on Fig. 1a are the 16 federal states and 401 districts, noting that for the three city states (Berlin, Bremen and Hamburg), the district area is equivalent to the state area. Plotted in the background of this figure is the elevation (Bundesamt für Kartographie und Geodäsie, 2016). The southern region of Germany lies at the foothills of the European Alps, with a maximum elevation of 2962 m a.s.l., with a transition to lower-lying floodplains in the north, interrupted by some low mountain ranges (*German: "Deutsche Mittelgebirge"*) in the centre of the country.

2.1.1. Climatological data

Monthly rasters of *P* and potential evapotranspiration (ET_o) at a spatial resolution of 1 km were downloaded from the Deutsche Wetterdienst (*English: German Meteorological Service*) portal: https://opendata.dwd.de/. The monthly *P* rasters are derived using an inverse distance weighting (IDW) procedure given the very high station density throughout Germany. The monthly ET_o rasters from the Deutsche Wetterdienst are derived using different approaches: the Wendling (1995) method for rasters from 1961 to 1990 and the AMBAV model (Löpmeier, 1994) for rasters from 1991 to 2020. To avoid step-changes in the ET_o values that could occur due to the transition between datasets, a bias correction procedure was applied to acquire consistent ET_o estimates throughout the studied period before using them to force the mGROWA model and calculate drought indices. To downscale the *P* and ET_o rasters to the daily temporal scale required for modelling, daily station data from the same portal were used.

The mean annual *P* and ET_o over Germany for 1961–2020 are shown on Fig. 1b and c, respectively. Annual *P* varies from as low as 398 mm $year^{-1}$ in the north-east to as high as 3183 mm $year^{-1}$ at the foot of the European Alps near the Austrian border. Two spatial patterns are evident in Germany: a positive gradient between increased elevation and increased *P*; and a reduction in *P* as the climate transitions from temperate (north-west) to cold (south-east). The mean annual ET_o presents a strong inverse relationship with elevation, with the lower *T* at high elevations leading to reduced ET_o values. Of note are the substantially higher values of ET_o in the south-west, mainly in the areas near the Rhine River.

2.1.2. Soil data

The Bodenübersichtskarte 1:200,000 (*English: Soil Overview Map*) for Germany (Krug et al., 2015) was used to characterise how the soil type and properties vary throughout Germany both spatially and with depth. Fig. 1d maps the dominant soil type over the uppermost 30 cm, showing a prevalence of sandy soils in the north, silty soils in central Germany, and a mixture of soil types in the south. Because the soil type may change with depth, in some areas the soil type in the lower soil layers modelled differs to what is presented on Fig. 1d. Values for the field capacity and effective field capacity varying both spatially and in the soil profile were also extracted from the Soil Overview Map.

The depth of the groundwater table plays an important role in the determination of the irrigation requirements because plants can obtain water from this source when the water table is relatively shallow. The spatial map of the mean groundwater depth (when existing in the uppermost 2 m) is based on the soil horizon descriptions, while the interannual fluctuations are based on the depths of gley horizons with reduced conditions. Fig. 1e shows the minimum groundwater depths, which corresponds to the summer months. Near-surface groundwater is most prevalent in the north-west regions bordering the North Sea, in the Hessian Ried in the south-west along the banks of the Rhine River, and in the north-east along the Elbe, Spree and Havel Rivers.

2.1.3. Agricultural data

Agricultural areas were extracted from the Digital Landbedeckungsmodell für Deutschland 2015 (Bundesamt für Kartographie und Geodäsie, 2015, *English: Digital Land Cover Model for Germany*); they

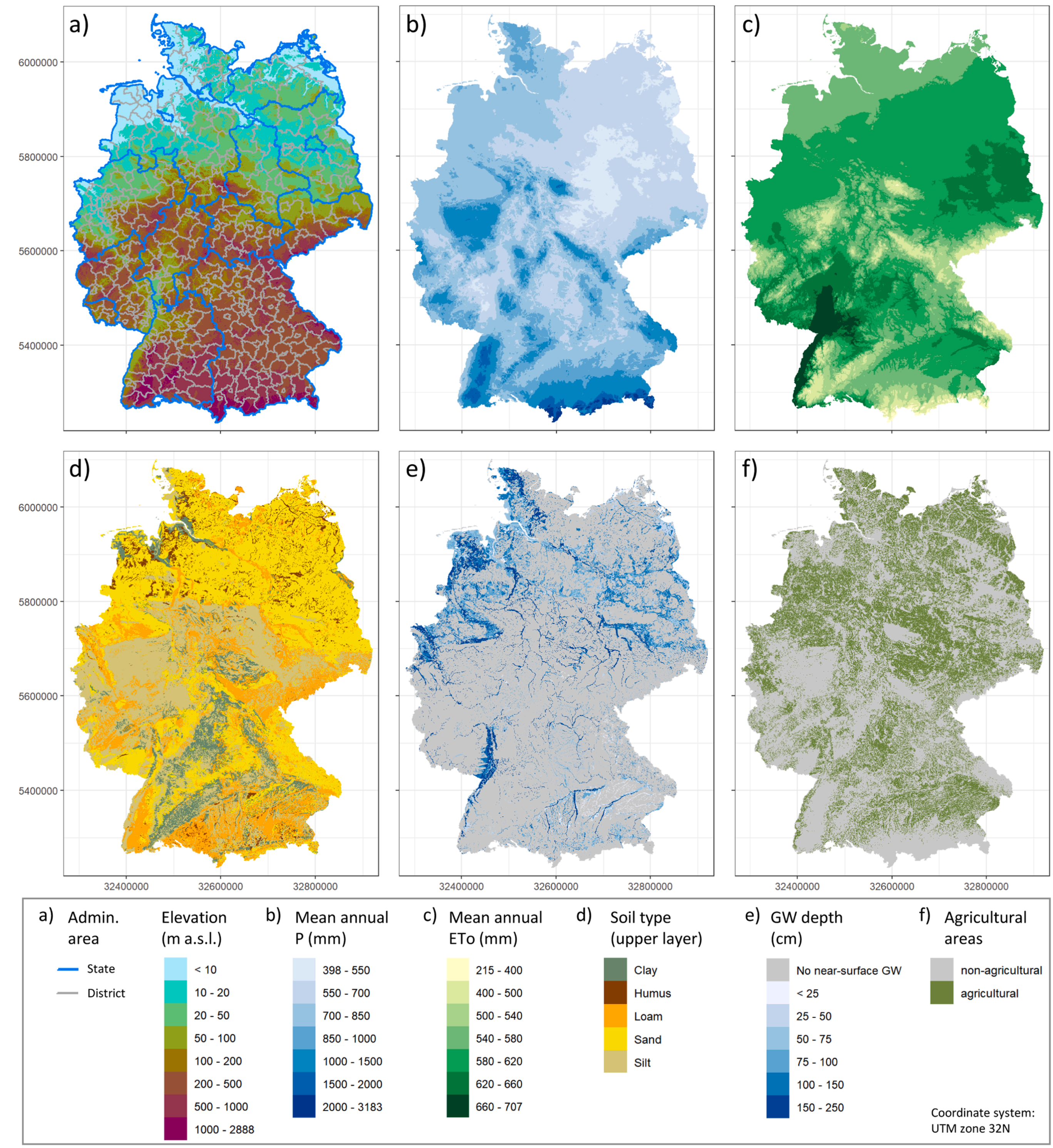

Fig. 1. Study area: *a*) federal states, districts and elevation (Bundesamt für Kartographie und Geodäsie, 2016); *b*) mean annual precipitation (1961–2020) (DWD Climate Data, 2020); *c*) mean annual potential evapotranspiration (1961–2020) (DWD Climate Data, 2018); *d*) soil types (Krug et al., 2015); *e*) groundwater depth over the summer months (derived from Krug et al., 2015); and *f*) agricultural areas (Bundesamt für Kartographie und Geodäsie, 2015). All data have been resampled to the 200 m model grid.

cover 36.9 % of the country and are shown on Fig. 1f. The agricultural areas selected only include the land classes denoted as croplands, with areas designated as pastures, meadows, vineyards and fruit trees excluded. Agricultural areas are spread throughout the country, but are more prevalent in the northern regions. The areas are mainly located in the lowlands, with few agricultural areas in highlands such as the Bavarian Alps, Black Forest, Harz and Rothaar Mountains.

Three datasets were then used for the determination of the spatial distribution of crop types: .

(a) the 2020 agricultural census from German statistical office (Destatis, 2021a) tabulates the areas covered by each crop type at the state level;

(b) the 2019 dataset provided by Blickensdörfer et al. (2022) maps 24 agricultural land cover classes in Germany through the application of a random forest classifier using remotely sensed and environmental data; and
(c) the 2021 census of vegetables and strawberries (Destatis, 2022) tabulates the areas covered by different types of vegetables and strawberries at the state level.

Data listing the areas equipped for irrigation at the district level were acquired separately from the corresponding databases for each of the 16 federal states.

2.2. Methods

A six-step methodology (Fig. 2) was implemented to assess irrigation estimates for Germany as a function of climatic conditions: 1) determination of the spatial distribution of crop types; 2) derivation of daily simulated irrigation requirements through the process-based model mGROWA; 3) calculation of SPEI-6, with the accumulation period reflecting the crop growing season; 4) determination of representative theoretical irrigation requirements for typical near-normal and dry years through assessing the relationships between SPEI-6 and simulated irrigation requirements; 5) allocation of which modelled agricultural areas are considered to be equipped for irrigation; and 6) determination of estimated irrigation quantities for near-normal and dry conditions over areas equipped with irrigation infrastructure. Each of the six steps of the methodology are described below in more detail.

In this work, *simulated irrigation requirements* refer to the mGROWA model outputs, which are expressed as a depth of water for all modelled grid-cells. *Theoretical irrigation requirements* refer to the quantities estimated for the near-normal and dry conditions, which are expressed as an average water depth for all crops over a district. Finally, the *estimated irrigation quantities* refer again to the quantities estimated for the near-normal and dry conditions, but this time only for grid-cells that are equipped with irrigation infrastructure. They also represent an average depth over the district.

2.2.1. Mapping crop distribution

Ten crop classes were modelled: wheat, winter barley, rye/triticale/oat, early season potato, late season potato, sugar beet, maize, rapeseed, shallow-rooted vegetables and deep-rooted vegetables. Due to the high similarity in plant structure and growing season, the rye, triticale and oat are classified as one crop class. Also, as a frequently irrigated crop, strawberries have been included within the category shallow-rooted vegetables. Together, the 10 modelled crop classes cover 86.7 % of the agricultural area in the country (Destatis, 2021a), and effectively all irrigation is used for these crops (Dietrich et al., 2015).

Information from the Bundesamt für Kartographie und Geodäsie (2015) was used to define the locations of all grid-cells that were modelled as agriculture. The statistics presented in Destatis (2021a) were then used to determine the percentage of agricultural land covered by each of the selected crops within each federal state (NUTS-2 level). Additionally, areas with potatoes were divided equally into early season potato and late season potato and data from Destatis (2022) was used to further categorise vegetables into shallow and deep-rooted vegetables. The 2019 dataset from Blickensdörfer et al. (2022) was used to incorporate the spatial variability of crop distribution within each federal state. Because the census statistics from Destatis (2021a) can be considered as the most reliable dataset, an iterative process was implemented to optimise the agreement between the spatial distribution of each crop within the district level and the total areas reported at the state level, assigning a specific crop type to each grid-cell classified as agriculture. As a result, a spatial distribution of crop types was obtained that: *i*) matches the state-level statistics presented in Destatis (2021a); and *ii*) reflects the spatial distribution of crop types from Blickensdörfer et al. (2022) within each state. Given that historical data are not available for a reliable reconstruction of the annual variations in crops planted, an assumption was made that the derived spatial distribution of crop types remained constant over the full modelled 60-year period.

2.2.2. Implementation of the mGROWA model to simulate irrigation requirements

The mGROWA model is a one-dimensional conceptual hydrological water balance model that was developed to assess the water balance over large regions over long temporal periods. It computes the water balance at the daily scale within multiple modelled layers of soil, considering bare soil evaporation, transpiration, capillary rise and seepage processes (Herrmann et al., 2013). All input datasets for the model are generated in raster form with the same spatial geometry (200 m resolution for this study). For a detailed description of the mGROWA model, the reader is referred to Herrmann et al. (2015). The irrigation module in mGROWA works in conjunction with the daily water balance model, and has been successfully implemented to calculate irrigation requirements in north-west Germany (Herrmann et al.,

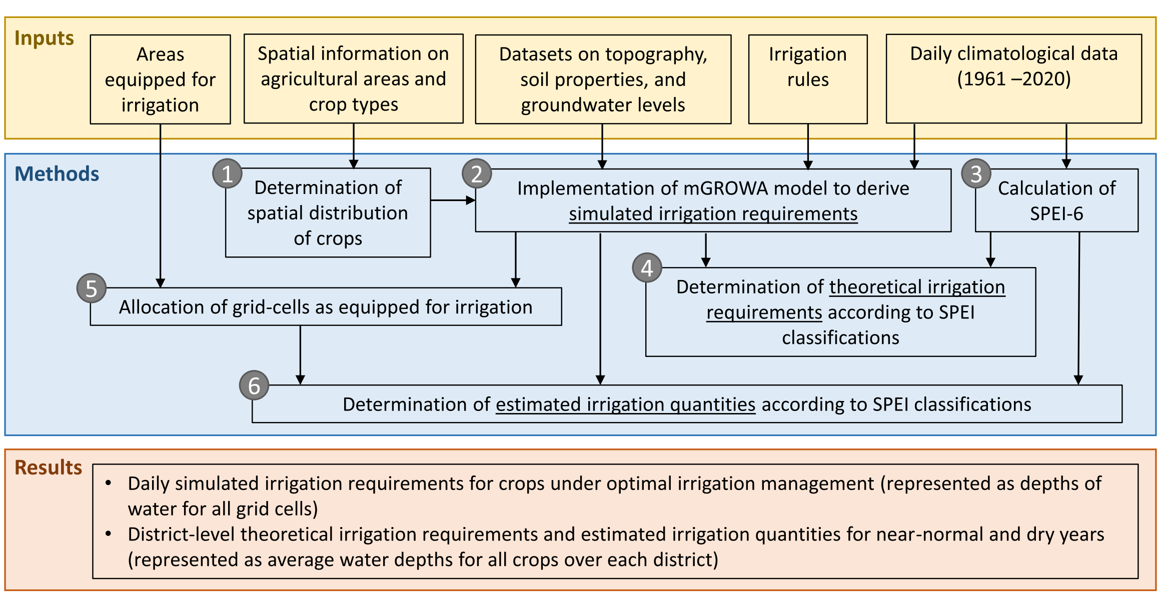

Fig. 2. Overview of methodology.

2016) and Thessaly, Greece (Pisinaras et al., 2023).

To generate the daily P and ET_o fields required as a model input, the monthly P and ET_o rasters were disaggregated to the daily scale by considering the temporal distributions of the variables recorded by the nearest station to each grid-cell. In addition, the ET_o values were corrected by a locally calculated topography factor based on Golf (1981), which considers slope and exposition (Kunkel and Wendland, 2002). Each crop was assigned monthly crop coefficients (k_c) for the calculation of daily actual crop evapotranspiration ($ET_{c\ act}$), using the FAO56 crop coefficient approach (Allen et al., 1998). As local climate conditions influence k_c values (Pereira et al., 2021), we adopted those presented in Engel et al. (2012) and Zinkernagel et al. (2022), which are specific for Germany. These k_c values are slightly higher than those derived for different climatological conditions (e.g., Allen et al., 1998). The monthly k_c factors are listed in Table 1, noting that the values of 0.65 characterise the bare soil evaporation for months where no crop exists. The model accounts for the extraction of water from multiple soil layers through a "*consumption depths*" parameter for transpiration that reflects the varying depths from which water is transpired based on the root structure of the crop. Also, the Disse function (Disse, 1995) is used to determine the dependence of evaporation on soil moisture, with the vegetation specific factor (r) set to 5 for agriculture.

The mGROWA irrigation module applies water to the cells according to user-defined rules, which were set to reflect standard irrigation practices in Germany. During the designated irrigation window, if the volumetric soil water content (VSWC) averaged over the root zone drops below a threshold value, irrigation is applied until either a target soil moisture level is reached (set here as 80 % of plant available field capacity for the crops and 100 % for the vegetables) or until a daily maximum irrigation limit is applied (set here as 40 mm for sugar beet, 20 mm for vegetables and 30 mm for all other crops). Effects of irrigation efficiency were not considered, and water availability for irrigation was considered as unlimited. Table 2 lists the irrigation windows and monthly root zone depth and VSWC threshold at which irrigation is applied for each crop class. The rules for the eight non-vegetable crops are adopted from Herrmann et al. (2016), and those for the two classes of vegetables were based on values reported in DWA (2019) and Zinkernagel et al. (2022). In addition, the model includes a pseudo-forecasting system to imitate operational practices, where no irrigation application is modelled if $P > 5$ mm is recorded for the day of or day after the VSWC drops below the threshold value.

For this study, the mGROWA model was run for the hydrological years 1961–2020 (i.e., 01/11/1960–31/10/2020) at the daily scale over all agricultural areas in Germany that were assigned one of the 10 crop groups listed in Table 1. The model grid has a spatial resolution of 200 m, with 2,855,242 grid-cells representing the agricultural area of ca. 114,200 km^2. Each pixel therefore represents an area of 4 ha. The soil was modelled in seven discrete layers, each 30 cm deep. Although the maximum modelled root depth is only 90 cm (Table 2), the seven layers were modelled because mGROWA also considers capillary rise from deeper soil layers with available water, as well as from the groundwater table over areas where it is sufficiently close to the surface (Fig. 1e).

2.2.3. SPEI-6 calculations

In studies of agricultural systems, it is important to consider the climatological water balance in the characterisation of meteorological drought (Stagge et al., 2015). Many studies demonstrate that the SPEI (Vicente-Serrano et al., 2010; Beguería et al., 2014) correlates well with both soil moisture measurements, particularly during summer months, as well as agricultural yields and crop water requirements (e.g., Vicente-Serrano et al., 2012; Zhang et al., 2015; Tian et al., 2018; Qin et al., 2023). The SPEI is a multiscalar drought index that is calculated using the climatological water balance (P - ET_o) and is especially suited to robustly consider the influence of recent trends in the evaporation demand in drought assessments. Because the irrigation period for the major crops in Germany spans from April to September (Table 2), the SPEI-6 calculated in the month of September was selected because it considers climatological inputs over this six-month period.

To calculate the SPEI-6 for September, for each district, the monthly spatially averaged values from April to September of accumulated P minus accumulated ET_o are calculated for each year, and a log-logistic distribution is fitted to the resulting data. This is then transformed to a normal distribution, meaning that the SPEI-6 indicates the number of standard deviations that the six-month accumulated P minus ET_o deviates from mean conditions. The SPEI calculations were performed using the R package *SPEI* (Beguería and Vicente-Serrano, 2017) and following the recommendation of the World Meteorological Organization (2017), a climate reference period of 1991–2020 was implemented for defining the probability distribution. The log-logistic probability distribution and the unbiased probability weighted moment for model fitting were adopted following the recommendations from Beguería et al. (2014).

2.2.4. Determination of theoretical irrigation requirements in near-normal and dry years

Having derived annual time series for both simulated irrigation requirements and the SPEI-6, the next step was to investigate the relationship between these parameters. For each district, the spatial averages of the annual simulated irrigation requirements were plotted against the corresponding SPEI-6 values and a loess regression (Cleveland et al., 2017) was applied using a span parameter of 1. From these regression curves, representative values of the annual theoretical irrigation requirements were extracted for both near-normal (SPEI-6 = 0) and dry (SPEI-6 = – 1) conditions. The spatial means only consider the land areas where one of the ten modelled crop classes is present. In addition to generating a greater understanding of the non-linear relationships between climate inputs and irrigation requirements in each region, such an analysis also provides a basis for rapid retrospective assessments of irrigation requirements to be made based solely on the climate input data.

Table 1
Monthly k_c factors for the modelled crops.

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wheat	0.65	0.65	0.90	1.00	1.15	1.45	1.40	0.65	0.65	0.70	0.65	0.65
Winter barley	0.65	0.65	0.85	0.95	1.30	1.35	1.25	0.65	0.65	0.85	0.65	0.65
Rye, triticale, oat	0.65	0.65	0.85	0.90	1.20	1.30	1.20	0.65	0.65	0.70	0.65	0.65
Early season potato	0.65	0.65	0.65	0.65	0.90	1.40	1.10	0.65	0.65	0.65	0.65	0.65
Late season potato	0.65	0.65	0.65	0.65	0.70	1.20	1.40	0.80	0.65	0.65	0.65	0.65
Sugar beet	0.65	0.65	0.65	0.65	0.65	1.00	1.40	1.30	1.30	1.10	0.65	0.65
Maize	0.65	0.65	0.65	0.65	0.65	0.90	1.15	1.05	0.80	0.65	0.65	0.65
Rapeseed	0.90	0.90	0.90	1.00	1.35	1.35	1.10	0.65	0.85	0.90	0.90	0.90
Shallow-rooted vegetables[a]	0.65	0.65	0.65	0.65	0.70	1.10	1.10	1.50	0.65	0.65	0.65	0.65
Deep-rooted vegetables	0.65	0.65	0.65	0.65	0.70	1.10	1.10	1.20	0.65	0.65	0.65	0.65

[a] Includes strawberries.

Table 2
Irrigation window for the modelled crops as well as the monthly values of root zone depth (RZD, in m) and volumetric soil water content (VSWC) at which irrigation is modelled (as percentage of plant available field capacity).

Crop	Irrigation window	April		May		June		July		August		September	
		RZD	VSWC	RZD	VSWC	RZD	VSWC	RZD	VSWC	RZD	VSWC	RZD	VSWC
Wheat	20/4 – 15/7	0.4	40	0.5	50	0.6	45	0.6	40	–	–	–	–
Winter barley	20/4 – 20/6	0.4	40	0.5	50	0.6	45	–	–	–	–	–	–
Rye, triticale, oat	20/4 – 20/6	0.4	40	0.5	50	0.6	45	–	–	–	–	–	–
Early season potato	20/4 – 30/6	0.4	40	0.4	50	0.4	45	–	–	–	–	–	–
Late season potato	15/5 – 30/8	–	–	0.4	10	0.4	40	0.4	50	0.4	45	–	–
Sugar beet	10/6 – 25/9	–	–	0.4	10	0.6	35	0.9	45	0.9	45	0.9	35
Maize	10/6 – 20/9	–	–	0.3	25	0.6	35	0.9	45	0.9	45	0.9	20
Rapeseed	20/4 – 15/7	0.6	40	0.7	50	0.9	45	0.9	40	–	–	–	–
Shallow-rooted vegetables[a]	01/6 – 15/8	–	–	–	–	0.3	70	0.3	70	0.3	70	–	–
Deep-rooted vegetables	01/6 – 15/8	–	–	–	–	0.6	70	0.9	70	0.9	70	–	–

[a] Includes strawberries.

2.2.5. *Allocation of which agricultural areas to consider as equipped for irrigation*

High spatial resolution data on areas equipped for irrigation are not available country-wide for Germany (Siebert et al., 2015). Using the district-level data acquired for each federal state, a simplified approach was adopted to transform the simulated irrigation requirements into estimated irrigation quantities. Within each district, the n modelled grid-cells with the highest mean annual simulated requirements were assigned as being those equipped with irrigation infrastructure, where the area covered by these n cells is equal to the area reported to have irrigation infrastructure. As a result, annual rasters of irrigation quantities were generated, with NA values for the grid-cells that were not assigned as being equipped for irrigation.

2.2.6. *Determination of estimated irrigation quantities in near-normal and dry years*

The same process described in Section 2.2.4 was again applied, but this time considering the simulated irrigation requirements only for the grid-cells designated as being equipped for irrigation. The results were then aggregated to derive the estimated irrigation quantities at the district level in near-normal and dry years. Furthermore, the derived values for 2009 were compared against reported irrigation extractions at the federal state level for the same year (Destatis, 2011).

2.3. *Software used*

The mGROWA model is implemented in Java, while the R Project for Statistical Computing was used for data preparation, analysis of results and the generation of figures, using the packages *terra* (Hijmans et al., 2022), *sf* (Pebesma, 2018), *SPEI* (Beguería and Vicente-Serrano, 2017) and *ggplot2* (Wickham et al., 2016).

3. Results

3.1. *Spatial distribution of crops*

Following the methodology described in Section 2.2.1, Fig. 3 shows the derived distribution of the modelled crops, presented as a percentage of the agricultural area in each district. Maize is grown mostly in both the north-west and south-east of Germany, wheat is more common in central Germany, and rapeseed, rye, triticale and oats in the east. Although potatoes and sugar beet cover a substantially smaller

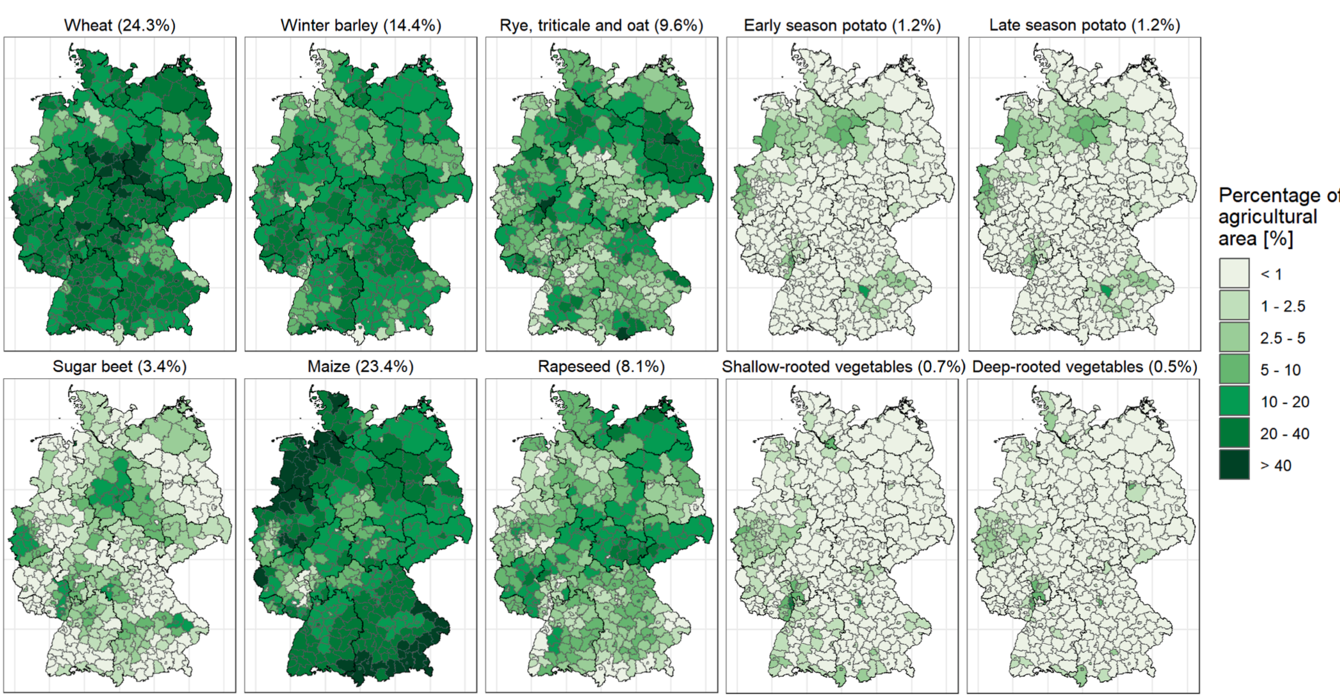

Fig. 3. Derived spatial distribution of the modelled crops across Germany, expressed as a percentage of the total agricultural area within the corresponding district. The percentages in the figure headings denote the percentage of agricultural area covered by the corresponding crop over the country.

percentage of the total area, the growing areas are heavily concentrated in the parts of Lower Saxony that have more irrigation infrastructure. Vegetables are grown more in the western and south-western regions. The total values do not add up to 100 % over each district because the modelled crops only comprise 86.7 % of the total crop area in Germany.

3.2. Simulated irrigation requirements for Germany

Fig. 4 visualises the daily water balance over one hydrological year (1988) for a representative grid-cell for which one of the crops (wheat) was modelled. Shown are the daily values of P, ET_o, $ET_{c\ act}$, percolation, water content in the root zone, and modelled irrigation application. The blue shaded area represents the irrigation window. Using the rules described in Table 2, irrigation is applied based on where the water content lies between permanent wilting point and field capacity shown on the fifth panel. This procedure is followed for all modelled grid-cells.

3.3. Irrigation requirements according to climate conditions

Fig. 5 displays the SPEI-6 values calculated for the month of September for the period 1991–2020, with the index calculated over each district. The figure highlights the spatial variations in climatic conditions over each summer vegetation period, as well as the extent to which such conditions prevail. For example, in 2011, the north-east of Germany experienced wetter than normal conditions while the opposite occurred in the south-west. In the extremely dry year 2018, the summer drought was substantially more pronounced in the northern half of the country. The same figure for the preceding 30 years (1961–1990) is provided in the Supplement (Figure S1), whereby the reference period 1991–2020 is still used, as described in Section 2.2.3.

The annual spatial means of simulated irrigation requirements for each district can be plotted against the corresponding SPEI-6 values calculated for September for each year. Fig. 6b to e show these scatter plots for the four districts displayed on Fig. 6a, which also shows the mean annual P - ET_o over the period 1961–2020. The scatter plots for the selected districts quantify the relationships between drier summers (lower SPEI-6 values) and increasing irrigation requirements. The loess regression curves added to these plots emphasise the non-linear relationships that exist, and show how this relationship differs according to district. For example, the change in gradient is substantially more pronounced for the district Düren than for Ostprignitz-Ruppin. The red triangles show how these fitted loess regression curves were used to identify representative values of mean theoretical irrigation requirements for near-normal (SPEI-6 = 0) and dry (SPEI-6 = – 1) years. This also enables rough estimates of irrigation requirements to be made based purely on information about the climate conditions of the year in question.

Using these representative values derived from the loess curves, Fig. 6f and g plot the spatial variation of the mean annual theoretical irrigation requirements for the near-normal and dry conditions, respectively. Most notably, there is a band of consistently higher theoretical requirements running from the north-east to the south-west. As expected, there is a strong consistency between the areas having higher theoretical requirements when they exhibit a negative climatic water balance over the summer months (Fig. 6a). Fig. 6h plots the absolute increase and Fig. 6i the percentage increase in theoretical irrigation requirements of a dry year compared to a near-normal year. The median percentage increase over the 401 districts is 72 %, with first and third quartiles of 60 % and 90 %, respectively. Interestingly, higher values of percentage change in requirements are observed in a band extending in the east-west direction across the centre of Germany compared to the areas immediately to the north or the south of this band. Districts with mean theoretical requirements lower than 25 mm year^{-1} in near-normal years were excluded from the plot of percentage increases, as small total increases in theoretical requirements for these districts in dry years can cause extremely high percentage values (Fig. 6e). For each of the ten

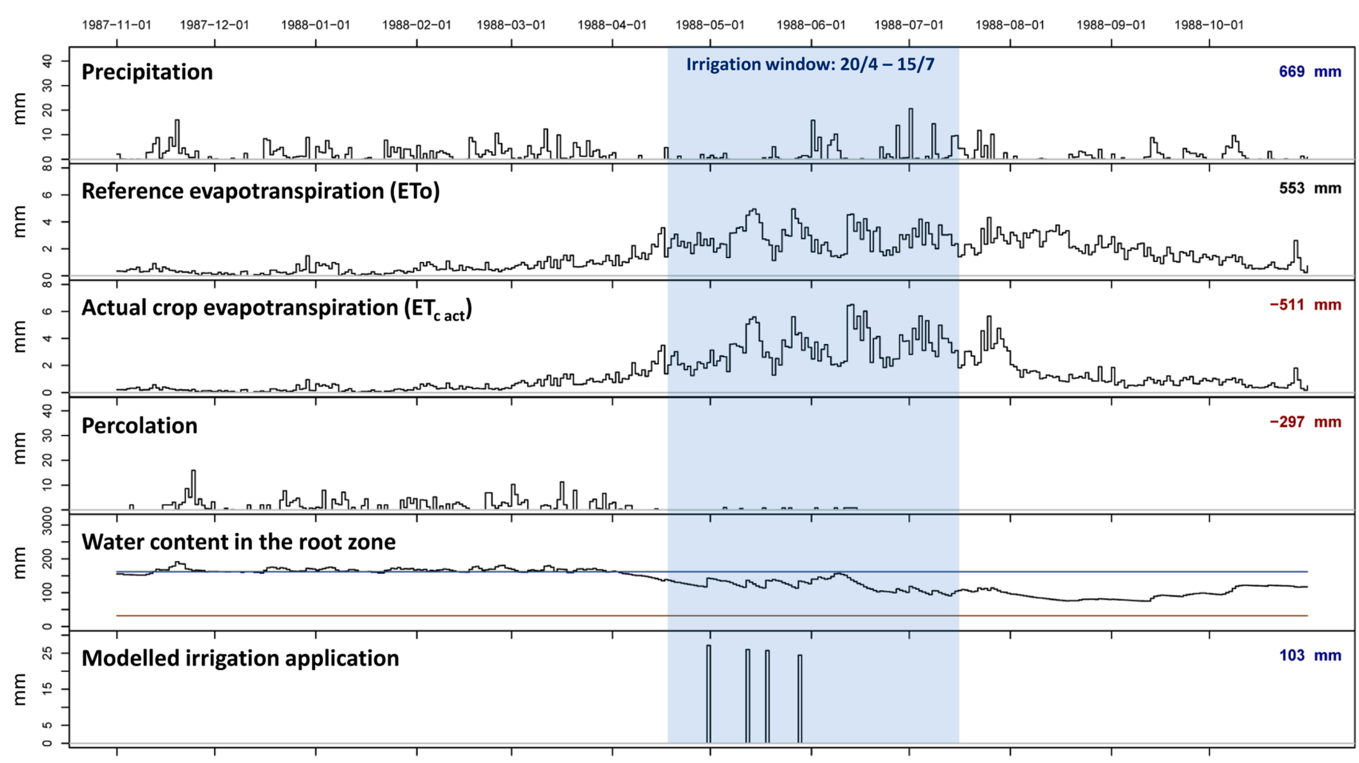

Fig. 4. Depiction of hydrological processes and irrigation application over the course of one hydrological year for a grid-cell modelled with wheat. The blue shaded area represents the irrigation window. In the fifth panel, the red and blue horizontal lines represent the permanent wilting point and field capacity, respectively. The values on the right represent sums over the hydrological year.

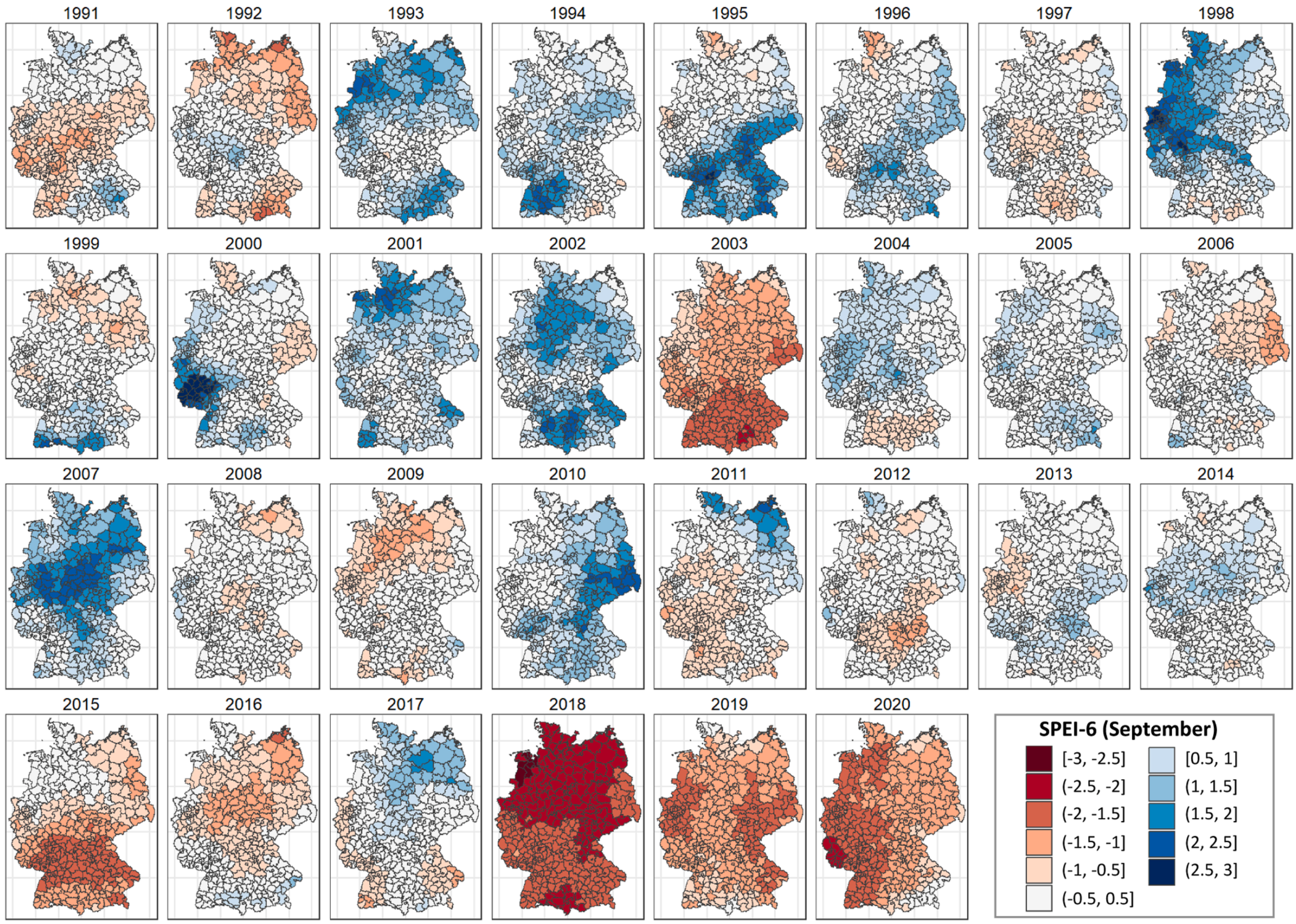

Fig. 5. SPEI-6 at the district level calculated for September for the years 1991–2020.

modelled crop classes considered in isolation, plots of the mean annual theoretical irrigation requirements for near-normal and dry years, as well as the percentage increases in requirements, are provided in the Supplement (Figure S2).

3.4. Transformation of simulated requirements into irrigation quantities

Fig. 7 illustrates how the results of the simulated irrigation requirements were converted to estimated irrigation quantities, with mean values for the period 1991–2020 displayed. Fig. 7a shows the mean annual simulated irrigation requirements for all modelled agricultural grid-cells over this period, meaning that each grid-cell has been assigned a specific crop type. The inset of an area in Lower Saxony shows the large spatial variations in estimates over a small area, which is predominantly explained by the varying crop types and heterogeneous soil properties. The percentage of agricultural area in each district that is equipped for irrigation is shown on Fig. 7b. Here, the largest concentration of irrigated infrastructure is in the central north (eastern Lower Saxony), with other notable areas in the south-west (Hessian Ried) and in the west (western North Rhine-Westphalia). It is important to note that this figure shows the percentage of agricultural areas that are equipped with irrigation infrastructure, not the percentage of total district area.

Fig. 7c shows the mean annual irrigation requirements (1991–2020) only for the modelled cells allocated as being equipped for irrigation after applying the procedure described in Section 2.2.5. On the map of Germany it is difficult to identify many areas of colour, because the areas equipped for irrigation comprise only 2.2 % of Germany (5.8 % of the agricultural area, which in turn covers 36.9 % of the total area). The inset illustrates the procedure over an area with a relatively high coverage of agricultural areas and irrigation infrastructure. Finally, the values of irrigation requirements only for areas allocated as being irrigated were converted into water volumes by multiplying annual simulated requirements by model cell size and summing to obtain total water quantities per district. These mean annual total irrigation quantities are presented on Fig. 7d, in megalitres (ML) per year. The districts with the highest annual quantities are concentrated in northern Germany, though some other isolated regions with high quantities are also evident. Because the total volumes are shown, smaller districts with intense irrigation are not as prominently displayed.

Table 3 lists statistics regarding the modelling results for the ten modelled crop types. The total area modelled and mean simulated irrigation requirements for 1991–2020 are shown in the first two columns. Note that because of the non-linear relationships between the SPEI-6 and the irrigation requirements (Fig. 6b to e), the theoretical values for SPEI-6 = 0 are typically lower than the mean values calculated for 1991–2020. The areas of each crop type that were allocated as being equipped for irrigation and the mean simulated irrigation requirements over these selected areas are also listed. Most notably, 82.7 % of shallow-rooted vegetables, 43.8 % of late-season potatoes, and 28.8 % of deep-rooted vegetables were assigned as being irrigated. Conversely, maize consistently presented low simulated irrigation requirements, and as such, only 1.5 % of its area was allocated to have irrigation infrastructure.

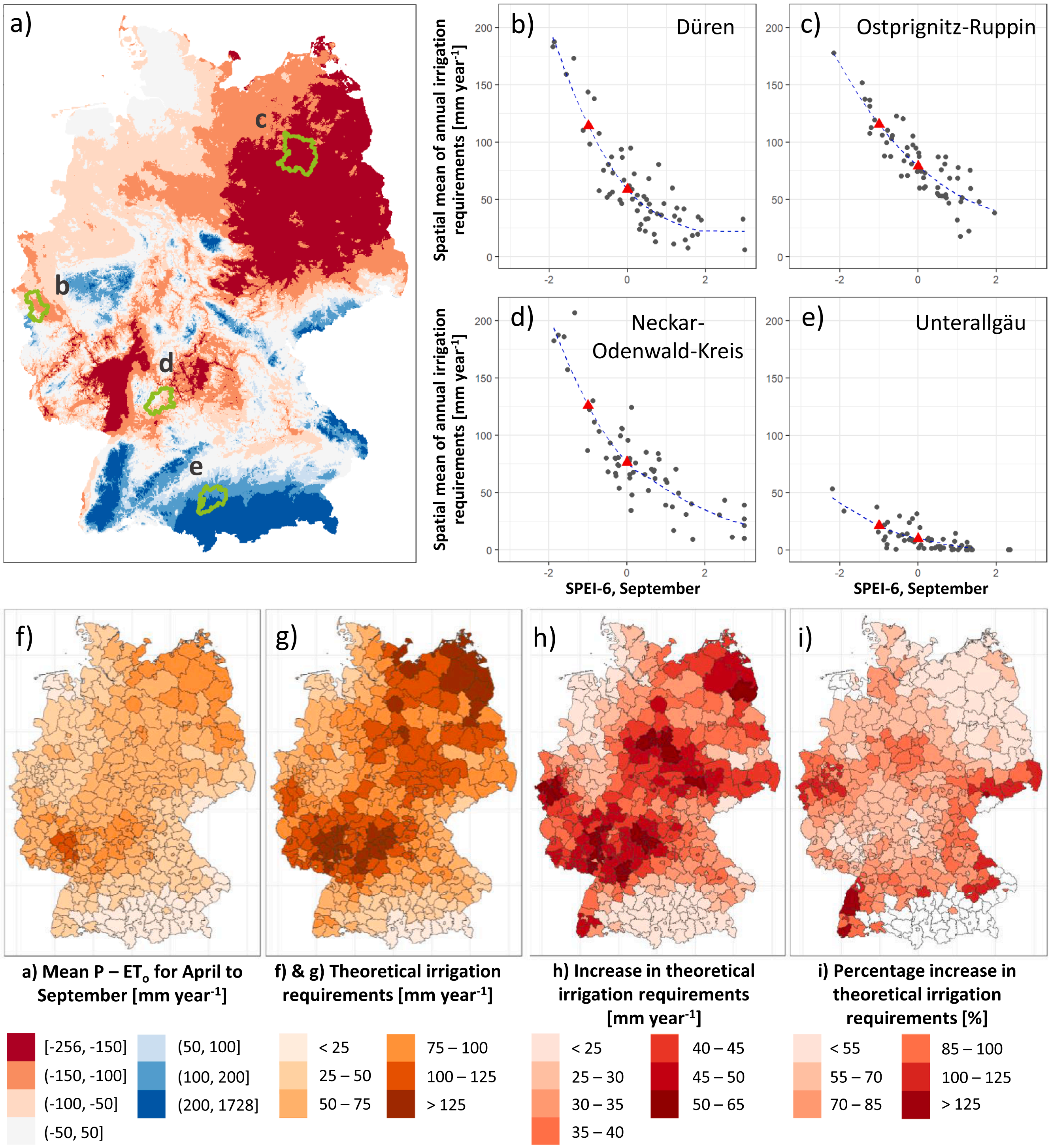

Fig. 6. *a*) Mean annual climatic balance (P - ET_o) for April to September for 1961–2020; *b*) to *e*) annual scatterplots of mean annual simulated irrigation requirements against the SPEI-6 calculated in September for four selected districts, with the red triangles showing the values considered as representative theoretical requirements for near-normal (SPEI-6 = 0) and dry (SPEI-6 = – 1) conditions; *f*) and *g*) mean annual theoretical irrigation requirements over agricultural areas for near-normal conditions and dry conditions; and *h*) and *i*) total and percentage increase in theoretical irrigation requirements per district in dry years compared to near-normal years. For visualisation purposes on *i*), only districts with mean theoretical requirements of >25 mm year^{-1} in near-normal years are shown.

3.5. Estimated irrigation quantities according to climatic conditions

Fig. 8a and b show the derived estimated irrigation quantities in ML for both the near-normal and dry years, respectively. These representative values were derived using the same loess curve fitting approach shown in Fig. 6b to e and the same span parameter, but this time using only the simulated values for grid-cells assigned as being equipped for irrigation (Fig. 7c). To better quantify the strain that these irrigation requirements place on available water resources, these same results are plotted on Fig. 8c and d, this time divided by the corresponding district areas (i.e., entire area, not just agricultural area). These figures therefore represent the estimated water extractions for the agricultural sector, averaged over the district areas and expressed as depths in mm, meaning that they can be compared against other water balance components such

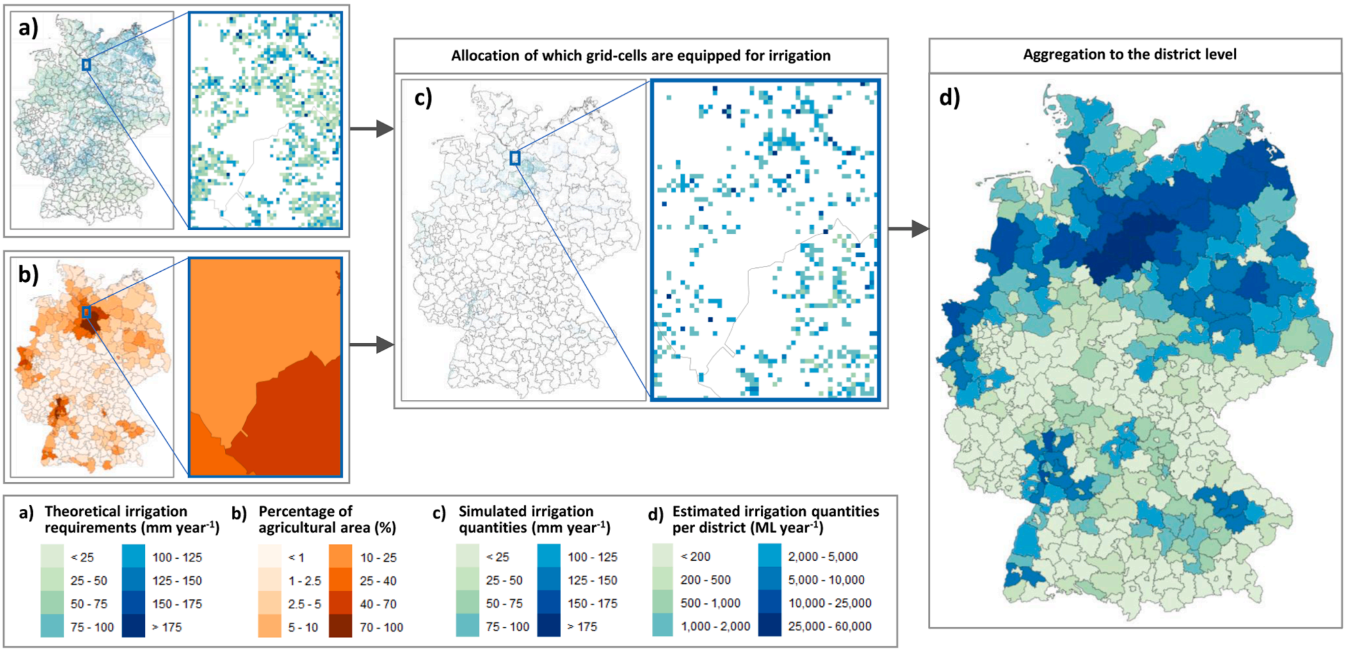

Fig. 7. Transformation of simulated irrigation requirements to estimated irrigation quantities: *a*) simulated irrigation requirements for all grid-cells modelled as agricultural areas; *b*) areas equipped for irrigation as a percentage of total agricultural area at the district level; *c*) simulated irrigation requirements only for the grid-cells assigned as being equipped for irrigation; and *d*) mean annual irrigation quantities (1991–2020, in ML) aggregated to the district level. For parts *a*) to *c*), the insets in the blue boxes show a zoomed in area in Lower Saxony.

Table 3
Irrigation statistics according to crop type.

Crop	All agricultural areas		Allocated as equipped for irrigation		
	Area modelled (ha)	Mean req. (mm)	Area modelled (ha)	Perc. allocated (%)	Mean req. (mm)
Wheat	3202,244	89	308,160	9.6	125
Winter barley	1891,032	62	52,468	2.8	87
Rye, triticale, oat	1270,566	58	55,520	4.4	76
Early season potato	155,928	60	27,948	17.9	78
Late season potato	155,920	97	68,332	43.8	116
Sugar beet	444,172	80	68,168	15.3	116
Maize	3078,708	32	47,212	1.5	55
Rapeseed	1068,212	82	48,692	4.6	128
Shallow-rooted vegetables[a]	85,788	166	70,940	82.7	174
Deep-rooted vegetables	68,408	92	19,712	28.8	112

[a] Includes strawberries.

as *P* or groundwater recharge, as well as allowing intercomparisons between districts. As expected, there is a strong similarity in patterns of the estimated irrigation quantities and the percentage of agricultural areas equipped for irrigation (Fig. 7b). As before, the marked increase in irrigation amounts between near-normal and dry years is pronounced. The results presented on all plots of Fig. 8 are tabulated in the Supplement (Table S2).

Table 4 compares the results for derived irrigation quantities against the values reported at the federal state level for 2009 (Destatis, 2011), the only year in the last two decades for which such values are reported. For 12 of the 14 states for which data are available, the reported irrigation application lies between the mean simulated irrigation over all agricultural areas and the mean simulated irrigation over grid-cells assigned as equipped for irrigation, meaning that these results can be considered to be highly plausible. This is because the agricultural areas actually irrigated would likely correspond to those with above-average simulated requirements, yet at the same time would not map 1:1 to those with the highest simulated requirements. For this reason, the uncertainty in the results is expected to be higher in states where only a very small percentage of the total agricultural area is equipped for irrigation. In the two northernmost states (Mecklenburg-Western Pomerania and Schleswig-Holstein), the reported application is lower than the mean simulated irrigation over all agricultural areas, which suggests that the model could be slightly overestimating irrigation requirements in the north. It is also worth noting that water extraction limits for agriculture are commonplace in some states, which is a likely reason why the modelled irrigation application is substantially higher than the reported amounts for states such as Mecklenburg-Western Pomerania and Brandenburg.

The column with the percentage of area equipped that was actually irrigated in 2009 shows interesting results, with values ranging between 27.6 % and 76.0 %. The irrigation census for 2019 (Destatis, 2021a reported the areas equipped for irrigation and areas actually irrigated (but not the total amount), and in this year, a similar range of 31.3 % to 77.5 % was reported. As seen on Fig. 5, 2009 and 2019 were slightly dry and very dry years, respectively, and there is no information available as to why so many areas equipped for irrigation were not actually irrigated in these two years. Based on this information, it is evident that the method implemented to convert simulated irrigation requirements to irrigation quantities should lead to an overestimation of actual irrigation quantities, because irrigation is considered to take place on all of these areas equipped (assuming that a simulated requirement exists in the corresponding year). Therefore, the results presented on Fig. 7d and Fig. 8 represent upper limits of actual irrigation quantities.

4. Discussion

4.1. *On quantifying irrigation requirements in Germany*

Irrigation requirements in Germany are driven by a multitude of factors. Most notably and as expected, irrigation requirements are

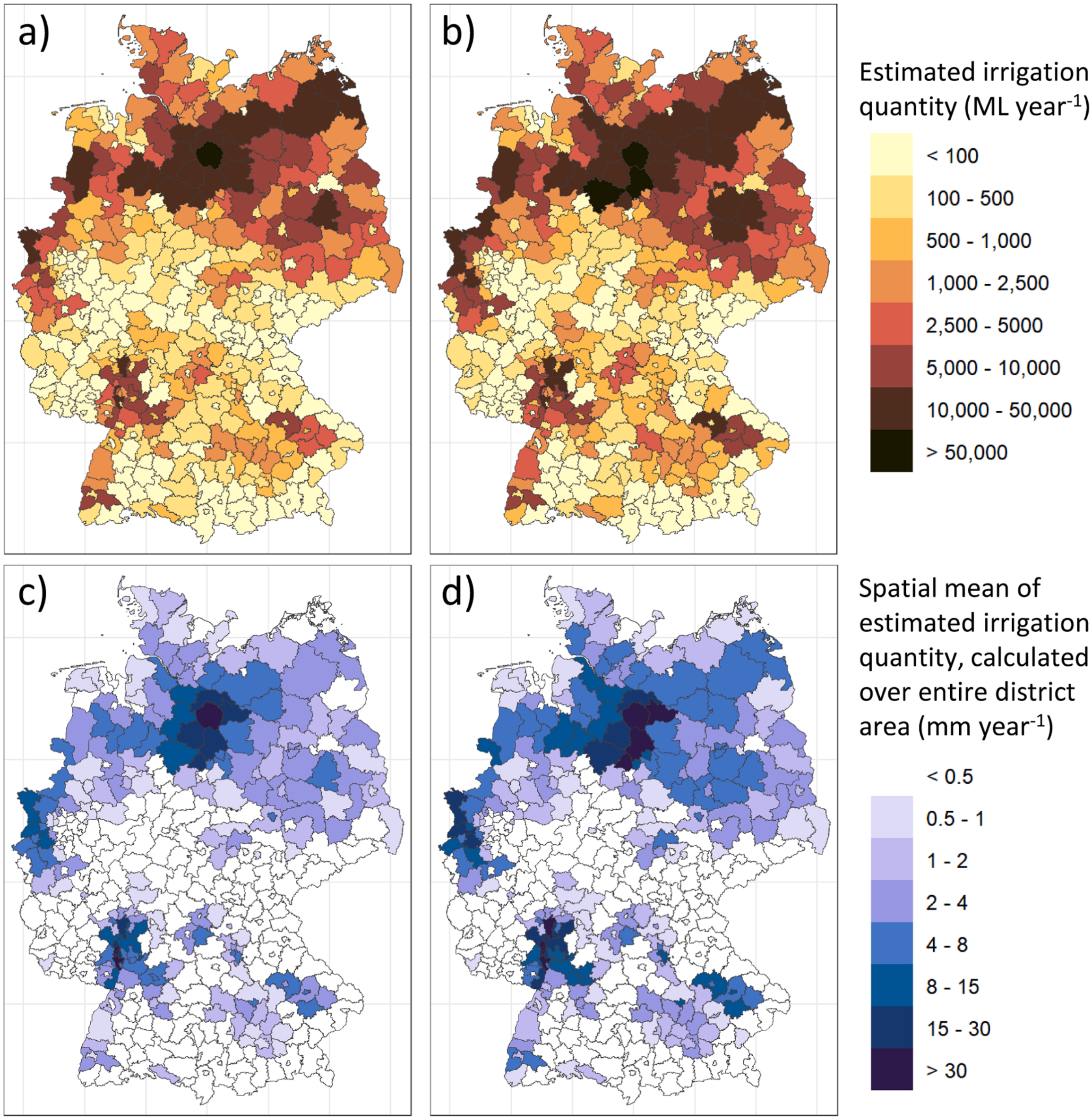

Fig. 8. *a*) and *b*) Estimated irrigation volume per district for near-normal (SPEI-6 = 0) and dry (SPEI-6 = – 1) conditions. Parts *c*) and *d*) show the same, this time expressed as a depth divided over the entire district area.

lowest in the regions with the highest *P* such as in south-east Germany (Fig. 1b). The effect of decreasing *P* in northern Germany when moving from the north-west to the north-east is also evident, with the irrigation requirements in the north-east furthermore increased because of low water retention properties of the light sandy soils that dominate this region (Drastig et al., 2016). Also, the theoretical irrigation requirements are very high in the Hessian Reid area in the south-west of Germany, which is in alignment with the high ET_0 in that region, demonstrating that the evaporative demand also plays an important role in addition to *P*. These areas of high theoretical irrigation requirements were also identified in the Germany-wide modelling undertaken by Drastig et al. (2016).

Previous studies modelling irrigation requirements in Germany (Table S1) incorporate a variety of spatial scales, time periods analysed, crops modelled and methods used to estimate irrigation requirements. Despite these differences, our results can still be compared against those from different studies to ascertain whether the irrigation requirements are similar. Mean annual values of requirements presented in Heidt (2009), Steidl et al. (2015), Herrmann et al. (2016) and Bernhardt et al. (2022) are all similar in magnitude to the mean annual requirements calculated over the corresponding regions in this study, those presented in Drastig et al. (2016) and Maier and Dietrich (2016) appear to be slightly higher than ours, and those in Riediger et al. (2016) are similar to ours in the north-east yet lower than ours in the north-west. Additionally, these studies all demonstrate similar levels of interannual and spatial variability of simulated irrigation requirements as well as variations in magnitude according to crop type.

This study and those mentioned in the previous paragraph all simulate irrigation requirements with the aim to optimise crop yield, whereas in practice, irrigation application also depends on economic factors and can be constrained by water extraction limits. Ostermann (2022) lists total irrigation water rights in seven districts in Lower Saxony, which are all very similar to the estimated irrigation quantities derived in this study for these districts for near-normal years. At the German-wide level, statistics for 2009 from state agencies throughout Germany were compiled by Dietrich et al. (2015), who then plotted the reported irrigation quantities at the district level and the ratios of crops irrigated at the state level on their Figures 18 and 19, respectively. 2009

Table 4
Comparison of reported and simulated water used for irrigation in 2009.

State	Reported values for 2009			Modelled values for 2009	
	AEI[a] (ha)	PI (%)[b]	MAI (mm)[c]	MSI (mm)[d]	MSI_AEI (mm)[e]
Baden-Württemberg	26,668	53.1	74	31	101
Bavaria	38,204	37.6	61	23	62
Berlin[f]	–	–	–	68	125
Brandenburg	38,960	54.1	72	71	126
Bremen[f]	–	–	–	36	116
Hamburg	1508	53.4	84	52	89
Hesse	32,244	48.4	91	54	94
Lower Saxony	313,693	69.8	77	59	114
Mecklenburg-Western Pomerania	30,408	48.0	97	98	152
North Rhine-Westphalia	61,384	46.0	66	52	94
Rhineland-Palatinate	32,032	62.0	109	56	120
Saarland	179	76.0	105	61	147
Saxony	11,794	27.6	62	35	110
Saxony-Anhalt	24,447	50.8	115	60	143
Schleswig-Holstein	21,904	31.8	54	64	138
Thuringia	5502	38.5	67	35	104

[a] Area equipped for irrigation (AEI). [b] Percentage irrigated (PI): the percentage of AEI that was actually irrigated in 2009. [c] Mean applied irrigation (MAI): the spatial mean of depth of irrigation applied over actually irrigated areas. [d] Mean simulated irrigation (MSI): The mean simulated irrigation requirements, expressed as a depth, over all agricultural areas. [e] Mean simulated irrigation depth calculated over areas equipped for irrigation. [f] Values not reported.

was classified as a near-normal year in southern and central Germany, and dry in north-western Germany (Fig. 5). The results for theoretical irrigation requirements according to SPEI-6 classification (Fig. 5c and d) show a high level of agreement with the values plotted by Dietrich et al. (2015), considering the climatic conditions across the country for that year. Here, it is also worth mentioning that the mGROWA model does not consider the question of irrigation efficiency. Furthermore, the method implemented to determine which crops are assigned as being irrigated resulted in a similar distribution (Table 3) to what was reported in 2009. The data used by Dietrich et al. (2015) are not publicly available.

The results demonstrate the extent to which theoretical irrigation requirements change throughout Germany as a function of the climatic water balance over the crop growing period April to September. There is a substantial non-linear increase in the irrigation requirements for the years with an SPEI-6 value of –1 compared to the requirements in near-normal years, which is consistent with results determined for China presented by Zhang et al. (2015) and Qin et al. (2023). Interestingly, the higher increases in theoretical requirements over the central belt seen in Fig. 6h correspond well to the silty soils in Germany (Fig. 1d), which suggests that soil properties strongly influence the irrigation requirements under dry conditions. We hypothesise that this is because the water retention time is smaller in sandy soils, meaning that irrigation is also required in near-normal years at frequent intervals, while over the silty soils, there is a more pronounced difference in soil water availability in years where there is an extended period of negative climatic water balance.

Although this study demonstrates the substantially increased irrigation requirements in dry years, this relative increase is not always reflected in the DWA-M 590, which acts as a guideline for determining water extraction limits in Germany (DWA, 2019). This guideline defines a dry vegetation period (also April–September) as one with a 20 % chance of occurring, which would in turn correspond to an SPEI value of –0.842. In such dry years, the tabulated irrigation quantities increase by approximately 20–25 mm for common crops, with minimal change in absolute quantity according to climate zone, soil properties or crop type. The results of this study show that at the corresponding SPEI-6 of –0.842, theoretical irrigation requirements would increase by more than this amount for: a) crops that already have requirements above approximately 75 mm in a dry year; and b) most crops in the silty soils in central Germany.

4.2. On uncertainties in estimating water use for irrigation

Decisions about which crops are to be irrigated are typically based on a combination of hydrological and economic considerations (de Witte, 2018), the latter of which is not reflected in the methodology of this study. In addition to which crops are irrigated, the question of water extraction limits plays an important role. For example, in Lower Saxony there is an extraction limit of 80 mm year^{-1} (Ostermann, 2022), while in other districts, water extraction limits vary according to individual user. For example, as seen in Figure 7 of Steidl et al. (2015), some user permits in Brandenburg can be in excess of 200 mm year^{-1}. In this study, no extraction limits were implemented, which could explain why the modelled irrigation application is consistently higher than that reported (Table 4). A search for scientific literature discussing illegal water extractions in Germany yielded no results; however, several news reports make reference to cases of illegal water extractions (e.g., Ems-Zeitung, 2018; Zeitung, 2022; Groß, 2023), though this does not appear to be widespread. There also exists the possibility that crops are deliberately underwatered to a point where the yield is not expected to substantially reduce. Unfortunately, there is no comprehensive information available regarding these points that allow limits to be confidently applied to the model to incorporate this information. Baroni et al. (2019) conducted surveys of numerous growers that use irrigation scheduling systems and reported that *"only in some cases were the recommendations actually implemented. In most of the cases, the users indicated that they applied different amounts of water compared to the recommendations provided by the systems"*.

In modelling irrigation requirements at such a high spatial resolution, the representativeness of the modelled site conditions for each grid-cell is an important consideration. Because of potential inaccuracies in input datasets, results for individual grid-cells are considered to be less reliable than the same results aggregated over larger areas. Furthermore, it is difficult to incorporate information about the percentage of areas equipped for irrigation that are actually irrigated in a given year. This varies according to state and year, and it is unclear from reported statistics whether the reason for so many areas not being irrigated is because sufficient green water was available, because of crop rotation practices, due to economic constraints, because of extraction limits or for other reasons (Siebert et al., 2010). In states where the percentage of area irrigated is actually quite low, the methodology implemented is more likely to result in discrepancies between the results and the reported statistics.

4.3. Planning for irrigation requirements in the future

Climate change projections consistently predict an increase in both mean summer and winter temperatures in Germany, while *P* changes are more uncertain. Some models show an increase and some show a decrease in summer *P*, while all show an increase in winter *P* (Huang et al., 2015; DWD, 2021). This study demonstrated the non-linear correlations between SPEI-6 calculated over summer months and the increases in irrigation requirements, and given the expected trends towards more frequent summer droughts in Germany (Naumann et al., 2018; Christidis and Stott, 2021), future irrigation requirements are expected to increase substantially. Additionally, changes in the temporal distribution of *P* over the crop growing season are also important, as potential longer spells between individual *P* events will also influence irrigation requirements. A subsequent step to the work presented here would be to run the mGROWA model over a selection of climate projections to derive a set of projected future irrigation requirements. Another consideration for the estimation of future irrigation requirements will be whether the cropping period is moved forward in the year.

The economic benefits of expanding the areas equipped for irrigation in the changing climate is expected to lead to a continued increase in the installation of irrigation infrastructure throughout Germany (Anter et al., 2018). As the vast majority of irrigation water in Germany (86.5 %) is extracted from groundwater resources (BMU/UBA, 2018), an important research question will be to determine whether increases in irrigation requirements can be supplied through potential increases in winter groundwater recharge as a result of increased winter *P*.

5. Conclusions

Using the hydrological water balance model mGROWA at the daily temporal scale, irrigation requirements were simulated for all agricultural areas in Germany at an unprecedented spatial resolution of 200 m, accounting for the spatial distribution of crops as well as crop-specific irrigation rules. The SPEI-6, calculated at the end of the irrigation period in Germany (September), was incorporated to determine the theoretical irrigation requirements at the district level according to near-normal and dry conditions. The use of reported statistics of areas equipped for irrigation at the district level enabled the simulated irrigation requirements to be translated into estimated irrigation quantities, aggregated to the district level. This is the first study within Germany that transforms simulated irrigation requirements to estimates of actual irrigation quantities at the district level.

This study demonstrates that climatic water availability, soil characteristics and crop type all largely affect irrigation requirements. When comparing the simulated requirements against the drought index SPEI-6, the relationship was shown to be non-linear, with the degree of non-linearity changing according to the region. Over a central band in Germany that is dominated by silty soils, the relative increases in theoretical irrigation requirements in dry years were shown to be substantially higher than for the surrounding regions with sandy soils. Regarding water allocation for irrigation, a comparison of the results from this study against guidelines for irrigation requirements in Germany highlighted that the guidelines do not always reflect the quantity of increased irrigation requirements in dry years.

This study has provided insights about how irrigation requirements change in response to climatic conditions, which is of paramount importance as the effects of climate change become more pronounced. In this regard, the results of this study can be used to support evidence-based planning for water resources management and to help avoid water use conflicts in Germany. This would support the maintenance of existing irrigation infrastructure as well as the planning of new technologies to help achieve sustainable water resources management. Additionally, the methods here described could be implemented in other regions worldwide to provide information related to irrigation water requirements.

CRediT authorship contribution statement

McNamara Ian: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Conceptualization. **Flörke Martina:** Writing – review & editing, Project administration, Methodology, Funding acquisition. **Uschan Thorben:** Writing – review & editing, Methodology. **Baez-Villanueva Oscar:** Writing – review & editing, Methodology. **Herrmann Frank:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2023.108641.

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