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To cite this article: Peter Greve *et al* 2023 *Environ. Res. Lett.* **18** 094020

ENVIRONMENTAL RESEARCH
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OPEN ACCESS

RECEIVED
17 March 2023

REVISED
24 July 2023

ACCEPTED FOR PUBLICATION
1 August 2023

PUBLISHED
17 August 2023

LETTER

Low flow sensitivity to water withdrawals in Central and Southwestern Europe under 2 K global warming

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Keywords: low flows, hydrology, water use, water demand, climate change, pseudo global warming

Supplementary material for this article is available online

Abstract

A sufficient freshwater supply is vital for humans, ecosystems, and economies, but anticipated climate and socio-economic change are expected to substantially alter water availability. Across Europe, about two-third of the abstracted freshwater comes from rivers and streams. Various hydrological studies address the resulting need for projections on changes in river discharge. However, those assessments rarely specifically account for the impact of various water withdrawal scenarios during low flow periods. We present here a novel, high-resolution hydrological modeling experiment using pseudo-global warming climate data to investigate the effects of changing water withdrawals under 2 K global warming. Especially in Western and Central Europe the projected impacts on low flows highly depend on the chosen water withdrawal assumption and can severely decrease under the worst case assumptions. Our results highlight the importance of accounting for future water withdrawals in low flow projections, showing that climate-focused impact assessments in near-natural catchments provide only one piece of the anticipated response and do not necessarily reflect changes in heavily managed river basins.

1. Introduction

Humans, ecosystems and economies require a sufficient and reliable supply of freshwater. However, water availability is limited, and several socio-economic sectors compete for the available water resources. Consequently, water withdrawals often take place at the expense of environmental flows, leading to degradation of aquatic ecosystems, loss of biodiversity, and depletion of groundwater resources (Arthington *et al* 2010, Wada *et al* 2010, Pastor *et al* 2014, Opperman *et al* 2019, Panagopoulos *et al* 2019).

Across Europe, representing one of the most developed and industrialized regions in the world, about two-thirds of the abstracted freshwater comes from rivers and streams (European Environment Agency 2020). Water availability generally follows a strong north-south gradient, resulting in abundant water availability in Northern Europe and lower river flows and scarce and seasonally-constrained resources in Southern Europe (Stahl *et al* 2010, 2012). An intensification of this pattern has been observed and attributed to anthropogenic climate change (Gudmundsson *et al* 2017). Under conditions of ongoing global warming this intensification will likely continue (Schneider *et al* 2013, Roudier *et al* 2015, Gampe *et al* 2016, Gosling *et al* 2016, Papadimitriou *et al* 2016, Donnelly *et al* 2017, Koutroulis *et al* 2018, Lobanova *et al* 2018, Greve *et al* 2018a), affecting hydrological droughts and low flows (Prudhomme *et al* 2013, Donnelly *et al* 2017, Marx *et al* 2018). Yet, little attention has so far been given specifically to the evaluation of the impact of future water withdrawals during low flow periods.

Substantial increases in water withdrawals in recent decades already pose major challenges to sustain a sufficient water supply and environmental flows in various regions worldwide, including parts of Southern Europe (Wada *et al* 2013, Pastor *et al* 2014). Next to the response to climatic changes, it is anticipated that river flows will alter in response to socio-economic changes (and associated changes in water withdrawals). As changes in water withdrawals are driven by economic and population growth and technological and societal developments (Flörke *et al* 2013, Wada *et al* 2016), in developed regions, water withdrawals from all sectors are commonly projected to further increase within the next decades. Depending on the underlying climate and socio-economic scenarios, those increases usually range between a few percent up to 100% (Brown *et al* 2013, 2019, Flörke *et al* 2013, Vandecasteele *et al* 2014, Wada *et al* 2016, Boretti and Rosa 2019). However, in scenarios applying optimal water use efficiency assumptions, public water withdrawals can decrease by up to 30% on average across Europe (Vandecasteele *et al* 2014). By additionally considering those changes in future water withdrawals, water supply and scarcity will be altered through a complex interplay of climate change and human interventions on available water resources (Wada *et al* 2011, Veldkamp *et al* 2015). Most hydrological studies focusing on river flows assess natural conditions—thereby not accounting for current and changing water withdrawals. Only a few studies explicitly include the feedback between projected water use estimates and river flows (Forzieri *et al* 2014, Koutroulis *et al* 2018, Lobanova *et al* 2018). Water use projections and scenarios are, however, diverse and are commonly based on the wide-range of available Shared Socio-economic pathways (SSPs). Different projections concerning population growth and economic development provided by the SSP scenario enable the design of various water use scenarios under different assumptions (Wada *et al* 2016). Variations of these scenarios have been used in different studies. It was, for example, shown that considering water withdrawals in hydrological models led to an additional reduction in minimum flows of up to 30% across Europe based on a combination of the Intergovernmental Panel on Climate Change 4th Assessment Report scenarios and an economy-first water management scenario (Forzieri *et al* 2014). Further, multiple warming levels and the consideration of different ad-hoc water use scenarios (based on SSP scenarios) and adaptation strategies are necessary to provide meaningful information to water managers and decision-makers (Koutroulis *et al* 2018), especially within the most affected regions in Southern Europe. Limited water resources are, however, not just a threat to southern Europe, as growing water withdrawals across different scenarios and anticipated changes in climatic conditions will likely exacerbate limited water supply and seasonal scarcity conditions in Central Europe as well (Schewe *et al* 2013, Forzieri *et al* 2014, Koutroulis *et al* 2018, Lobanova *et al* 2018, Greve *et al* 2018b). It is, therefore, essential to provide a step towards a more holistic assessment of anticipated river flows and their sensitivities to different water use scenarios under conditions of ongoing global warming.

2. Methods

2.1. Community Water Model

The hydrological simulations are generated using the Community Water Model (CWatM), a state-of-the-art large-scale rainfall-runoff and channel routing water resources model (Burek *et al* 2020). CWatM is process-based and used to quantify water supply, as well as human water withdrawals from different sectors (industry, domestic, agriculture) and multiple sources representing the effects of water infrastructure, including reservoirs, groundwater pumping and irrigation canals (see appendix A for more information and a detailed description of water use abstraction and parameterization in CWatM). CWatM is designed at grid level, with two native versions for 0.5° and 5′ resolutions at global scales (with sub-grid resolution taking topography and land cover into account). Here, we use the 5′ model version. It operates at daily time steps (with sub-daily time stepping for soil and river routing). CWatM is implemented as an open-source modular structured Python program, and requires daily meteorological input comprising precipitation, as well as surface air temperature, relative humidity, wind speed, surface air pressure, and incoming longwave and shortwave radiation. The latter quantities are required to estimate potential evaporation based on the Penman-Monteith method for a reference crop surface, including a crop factor accounting for different vegetation surfaces. Please refer to the model description for an overview on used input maps concerning topography, soil properties, reservoirs and lakes, etc and more details on the representation of hydrological processes (Burek *et al* 2020). We use here a calibrated version of CWatM. Calibration was performed independently from the experimental design of this study (see section 2.2) based on WATCH Forcing Data by making use of ERA-Interim reanalysis data (WFDEI) (Weedon *et al* 2014). The calibration procedure provides a default calibrated version of CWatM across Europe that can be used for multiple applications. A set of model parameters representing, e.g. snowmelt, soil, and routing characteristics, has been calibrated against 363 discharge time series from the Global Runoff Data Centre (GRDC) within the larger EURO-Cordex domain (see appendix D). From the set of 363 stations, only 283 are located within the smaller subdomain considered in this study (see figure 1), and 195

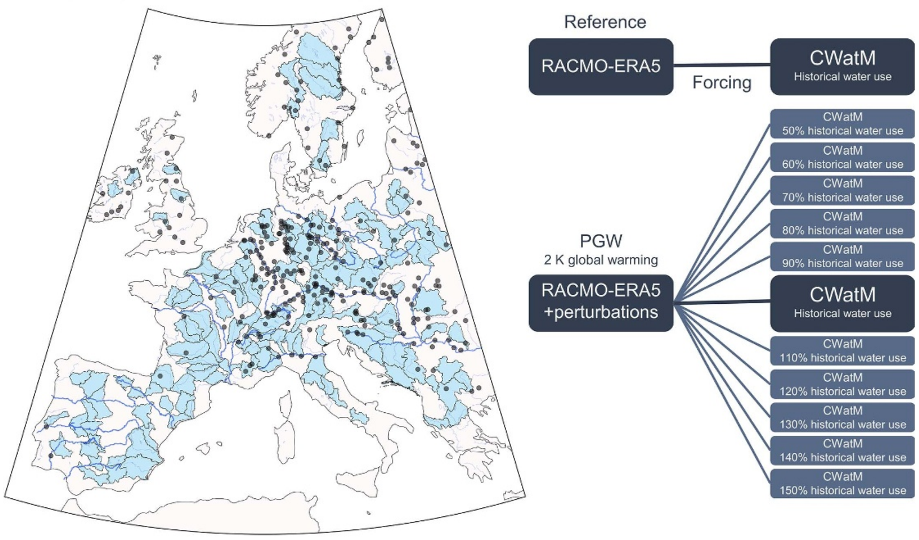

Figure 1. The model domain and an illustration of the experimental design. The subset of independent medium-sized river basins based on the European HydroBASINS data set (Lehner and Grill 2013) is highlighted and outlined in blue. The locations of 283 stations within the model domain providing observed discharge are illustrated as gray dots. The simulation period ranges from 1981–2010.

of those provide consistent time series of at least 25 consecutive years that are required for model validation (see section 3.1).

2.2. Forcing data

CWatM is forced by a novel pseudo-global warming (PGW) experiment within the period 1981–2010 (Aalbers *et al* 2023). PGW simulations are created by perturbing the atmospheric and ocean forcing data of regional climate model (RCM) simulations (Attema *et al* 2014, Prein *et al* 2015, Bouaziz *et al* 2021), to resemble historical weather patterns and events under globally warmer conditions, here 2 K (Kelvin) global warming with respect to 1991 to 2020. The simulations are based on the Royal Netherlands Meteorological Institute regional atmospheric climate model (RACMO; Meijgaard *et al* 2012), forced with the fifth generation of reanalysis data (ERA5) provided by the European Centre for Medium-range Weather Forecasts (ECMWF; Hersbach *et al* 2020). A non-perturbed reanalysis-driven simulation serves as a reference (see appendix B for more details). PGW experiments enable the assessment of climate change impacts, conditional on historical weather patterns (Prein *et al* 2016), droughts (Ullrich *et al* 2018), water supply (Li *et al* 2019), and ecosystem adaptation (Bouaziz *et al* 2021), among others. In our application, we adopted 2 K as the global warming level, closely resembling conditions usually featured in middle-of-the-road scenarios. We argue that, given the resemblance of the weather patterns in the historical and PGW simulations, minimizing the influence of natural variability, the PGW experiments provide a unique opportunity to assess the impact of water withdrawal scenarios on average and low flow discharge that remain recognizable to the user. This provides insights into adaptation and mitigation potentials, guiding the design of efficient, sustainable, and resilient water management interventions.

2.3. Low flows and the incremental adjustment of water withdrawals

CWatM provides the output of daily discharge within 30 years from 1981 to 2010. We will here assess mean daily discharge (Q_{avg}) and low flows (at the 10th, Q_{10}, percentile of the entire period). We argue that low flows at the 10th percentile best represent hydrological impacts relevant to water managers and end-users as they occur at time frames of several weeks. Long-term water planning and water management are crucial at such time frames. A rapid and localized response can often address extreme low flow conditions (e.g. at the 1st percentile) using practices such as deficit irrigation or emergency wells. However, dealing with weeks and months of scarcity requires, besides targeted measures to preserve existing water sources (including groundwater), strategic (often high-cost) investments such as large-scale reservoirs, efficient irrigation systems, or a careful selection of crop mix. Next to analyses at the grid cell level, we further focus on a set of medium-size river basins from the European HydroBASINS dataset (Lehner and Grill 2013) to investigate impacts at the basin scale. We selected 134 independent basins ranging between 5000 km^2 and 30 000 km^2 (with four basins larger than 30 000 km^2, see figure 1).

We performed simulations considering regular incremental adjustments of the historical water withdrawals (ranging between ±50% of historic water withdrawals) under PGW conditions. That range represents an ad hoc and simplified representation of multiple, possible future water management scenarios across developed regions, such as Europe (Brown *et al* 2013, 2019, Flörke *et al* 2013, Vandecasteele *et al* 2014, Wada *et al* 2016, Boretti and Rosa 2019). The narrative of these scenarios often follows SSP scenarios, representing the broad range of middle-of-the-road (SSP2) and sustainability (SSP1) scenarios (Wada *et al* 2016). In fact, across Southern Europe, even increases in water withdrawals beyond 50% can occur under more pessimistic scenarios, while decreases in water withdrawals might occur across Central Europe under more optimistic scenarios (Vandecasteele *et al* 2014, Wada *et al* 2016). Nonetheless, since 2 K global warming does more closely represent a middle-of-the-road global change scenario, we limit the possible range of changes in water withdrawals to ±50%. Please see figure 1 and appendix C for more information.

3. Results

3.1. Validation against observed discharge

One-hundred and ninety-five stations are used to validate the model's performance of Q_{avg} and Q_{10}. Given the scope and the experimental design of this study, our validation efforts focus on mean biases and errors in the distribution of daily discharge rather than day-to-day hydrological performance (figure 2). The observed mean discharge shows a negative bias (ca. −9%) and explained variance of 0.98. The scatter is more pronounced for the low flow statistics, especially evident through the relatively large root mean square error (RMSE) (45.3 m^3 s^{-1} at Q_{10}). Explained variance is reduced (0.968 at Q_{10}), but remains at a high level. A mean bias of ca. −13% is found for low flows at Q_{10}, pointing towards a dry bias. A median dry bias of ca. −18% is also found when considering the low segment volume of the flow duration curve (defined at the exceedance probability 0.7), while almost no median bias is found for the mid segment volume (exceedance probabilities ranging from 0.2 to 0.7, see supplementary table S1). Even though we solely consider long-term averages in the following analyses, explained variances are found to be high also at monthly levels (see supplementary figures S1 and S2). RMSE values are found to be smallest from September to December and largest from March to July. Mean biases are positive (up to ca. 25%) from May to July and negative especially from October to January (up to ca. −33%). CWatM also captures the overall timing of low flow conditions. Low flows primarily occur during summer in most Western, Central, and Eastern European basins and during late winter and early spring in more snow-dominated Northern European and mountainous catchments (see supplementary figures S3 and S4). More validation metrics are provided in supplementary figures S5 and S6. In summary, we conclude that the simulated discharge as obtained by CWatM and forced by historical weather provides a robust representation of Q_{avg} and Q_{10}, even though simulated discharge tends to show a dry bias concerning low flows. Relative differences are especially large in basins with low flows less than 50 m^3 s^{-1}. That includes basins that are either relatively small (<5000 km^2) and/or dry. Besides the focus on Central European basins within the calibration procedure (due to limited data quality in Southern Europe, see Methods) and various other factors (e.g. large relative discharge variability and high sensitivity of river flows in small basins to changing meteorological, seasonal, and climatic conditions potentially not captured in a distributed hydrological model), the dry bias contributes to our decision to consider an independent set of medium to large river basins across Europe (see figure 1).

3.2. Changes in average and low flows

While simulated differences in Q_{avg} between reference and PGW conditions assuming no change in freshwater use (see figure 3) generally resemble the well-known pattern of southern European drying and northern European wetting as determined through traditional climate model projections (Stahl *et al* 2010, 2012, ?), the high-resolution modeling approach used here reveals significant regional differences. For example, while declines in Q_{avg} are found in most regions and basins surrounding the Mediterranean Sea, some southern European regions do not show distinct decreases in Q_{avg} under conditions of 2 K global warming. These are primarily regions in mountainous northwestern Spain, as well as basins surrounding the northern Adriatic Sea. Increases in Q_{avg} are primarily found within the northeastern parts of the study domain and, to a lesser extent, in mountainous regions across Europe (e.g. the Alps). Most western and central European regions only show small relative differences in Q_{avg} (±10%). In contrast to Q_{avg}, the total extent of regions and basins showing declines in low flow conditions is considerable. This includes regions in western and southern Europe, that show no distinct changes in Q_{avg}. Nearly all basins across the entire Mediterranean Sea region show decreases in Q_{10} of at least 20%, revealing a more pronounced sensitivity of low flow conditions to 2 K global warming. Decreases in Q_{10} are also apparent in France, Belgium, the Netherlands, and the British Isles, contrasting the small projected changes in Q_{avg} for these regions. Increasing low flows are more pronounced than increases in Q_{avg} across Alpine regions and within the northeastern parts of the study domain. However, while relative differences between reference and PGW conditions are generally large (>20%) for low flows (please note the different scales in figure 3), it needs to be noted that absolute differences in low flows do not necessarily correspond to the absolute differences in Q_{avg} (see supplementary figure S7).

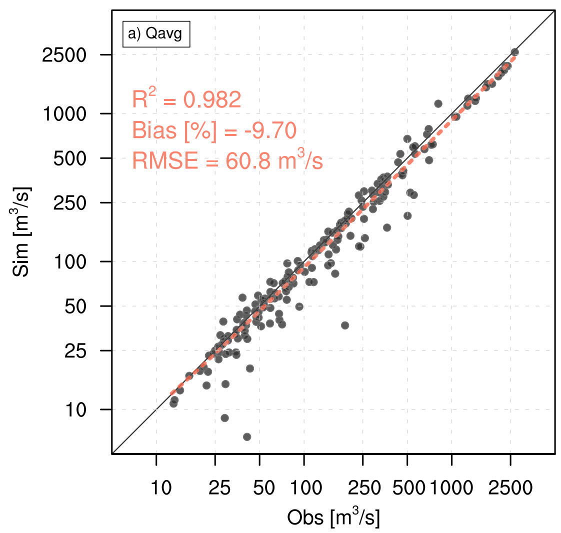

Figure 2. Validation of (a) Q_{avg}, and (b) Q_{10} of average daily simulated discharge against average observed discharge across Europe (see figure 1). Each dot represents a single station and simulated discharge statistics are estimated within the same time frames of observed data availability. At least 25 years of consistent streamflow measurements were necessary to estimate mean discharge and low flow statistics.

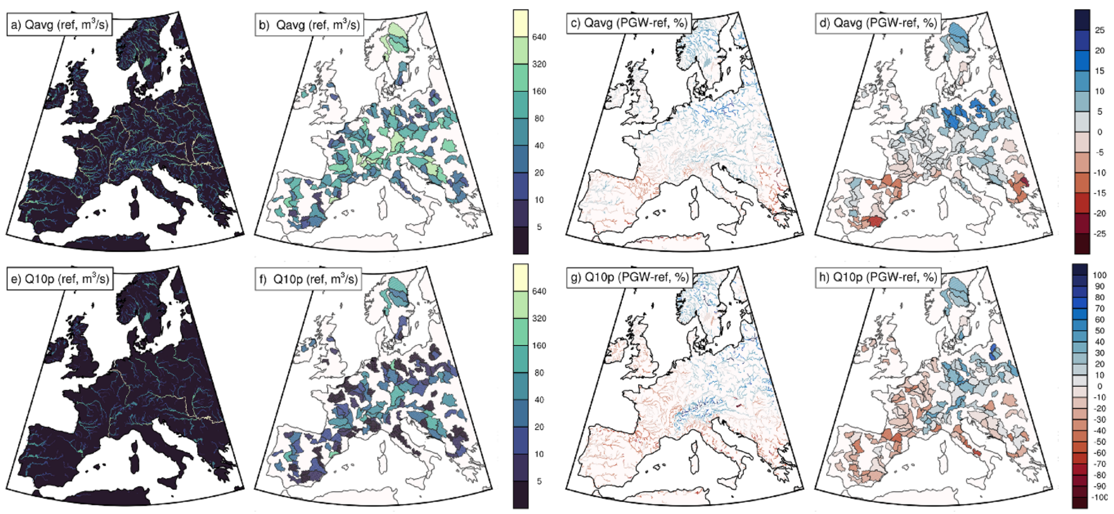

Figure 3. Mean discharge and low flows under reference conditions at grid scale (1st column) and at basin scale (2nd column). Relative differences in mean discharge and low flows between PGW and reference conditions at grid scale (3rd column) and at basin scale (4th column). Please note the difference in scaling between average discharge (top row) and low flows (2nd row). Grid cells and basins with $Q_{avg} < 10$ m^3 s^{-1} are not shown in columns 2, 3, and 4.

3.3. Sensitivity to adjusted water withdrawals

Before assessing the sensitivities of discharge statistics to changes in water withdrawals, it is important to note that discharge and low flows largely decrease linearly with increasing water withdrawals across Europe (see supplementary figures S8–10). However, the sensitivity to increasing water withdrawals is regionally different (see figure 4). Figure 4 thus shows that low flow sensitivities are highest in regions with large (upstream) water withdrawals (e.g. Central Europe) and can reach up to parity resulting in decreases of 10% in low flows per 10% increase in water withdrawals. Such high sensitivities are primarily located in upstream areas of rivers (e.g. Rhine, Meuse, Seine) in France, Benelux, and Germany. Relative sensitivities concerning average flows are considerably smaller. Only a few rivers and basins in parts of Eastern Germany reach maximum sensitivities in Q_{avg} up to -4% per 10% increase in water withdrawals. Sensitivities are generally largest in basins experiencing large water withdrawals (see supplementary figure S11) and main drivers of changes in mean and low flows in most Central and Western European rivers and basins are indeed industrial water withdrawals (that dominate total water withdrawals in these regions, see supplementary figures S12–15), while irrigation withdrawals locally impact southern European rivers.

We can further show that the response to varying levels of water withdrawals (within the range

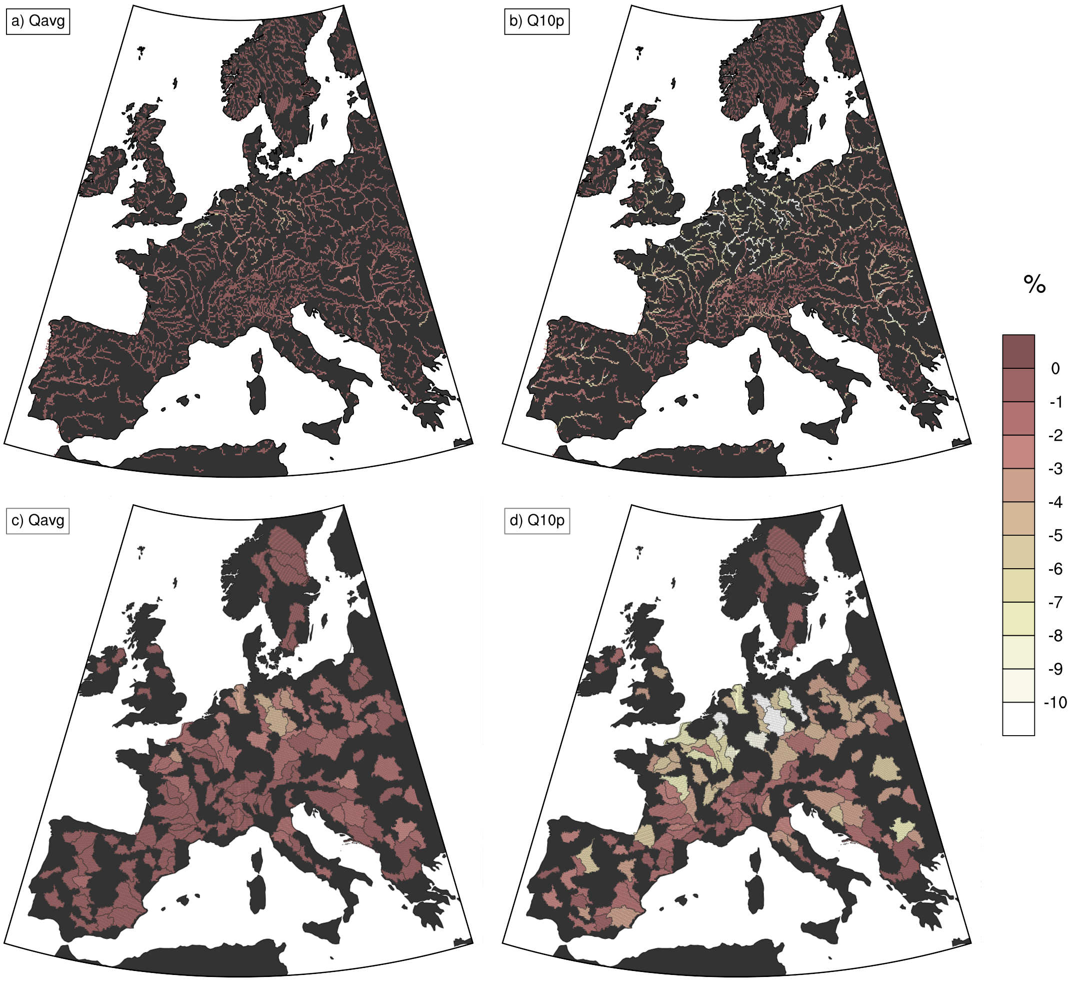

Figure 4. Sensitivity of mean discharge and low flows under PGW conditions to relative changes in water withdrawals at grid scale (1st row) and at basin scale (2nd row). The scale shows relative declines in (left column) Q_{avg}, and (right) Q_{10} corresponding to a 10% increase in water withdrawals. Grid cells with $Q_{avg} < 10\ m^3\ s^{-1}$ are not shown (dark gray). Also excluded are those grid cells where $R^2 < 0.9$ of the simulated discharge.

of ±50% of historic water withdrawals) exceeds the climate change response of 2 K global warming in average and low flows across many heavily managed basins in Central and Western Europe. Figure 5 illustrates the adjustment in water withdrawals that is needed to resemble projected changes in Q_{avg} and low flows under 2 K global warming. Anticipated climate-induced changes in average discharge are minor in most parts of Western and Central Europe (±10%). Therefore, future changes in average flow conditions will most likely be driven by changes in water withdrawals. The magnitude of climate-driven decreases in low flows in Western Europe (see figures 3(h) and (l)) is similar to low flow changes under conditions of increasing water withdrawals up to 50%. Hence, assuming increases in water withdrawals of 50% or less can regionally double or counteract the climate-only response. If differences of this magnitude also exist between water use scenarios, identified changes in low flow conditions can either be neutralized or amplified, thereby increasing uncertainties and hindering robust assessments. However, it is important to note that this assessment does not provide meaningful results in less-managed or near-natural basins. If human interventions and water withdrawals are negligible, the climate change response will dominate even if water withdrawals were extended or stopped entirely.

4. Discussion

By forcing a state-of-the-art large-scale hydrological model using a set of PGW experiments across a western European domain, we have obtained (i) novel insights into changes of average and low flow conditions under 2 K global warming and

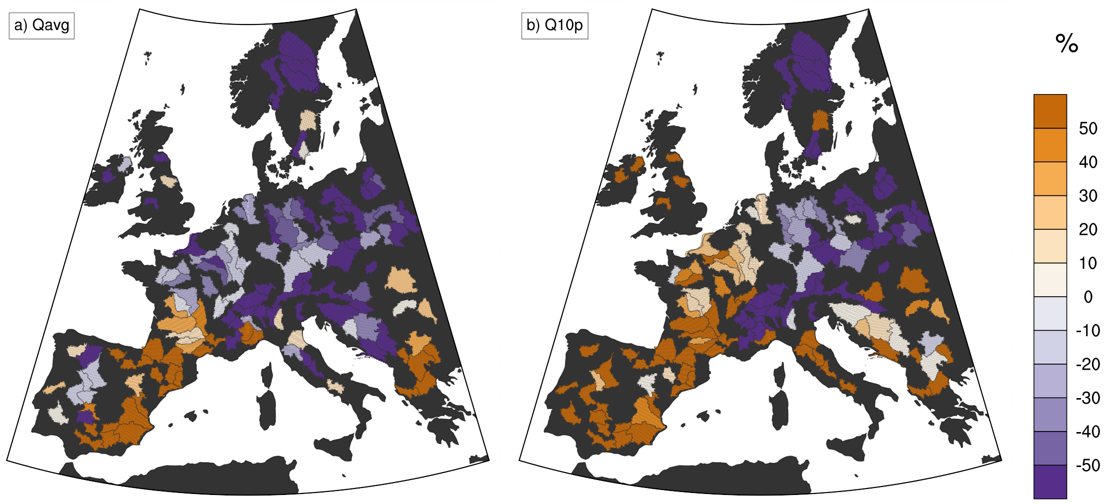

Figure 5. The change in water withdrawals (in %) that results in flow changes similar to those projected by the 2 K warming experiment (see figure 3) at basin level. Illustrated is the percentage of water withdrawals in reference to baseline conditions for (a) Q_{avg}, and (b) Q_{10}. Darkest colors denote all percentage values above/below 50%.

(ii) sensitivities to the range of possible alterations in future water withdrawals. While the obtained changes in discharge conditions generally correspond to established signals of Northern European wetting and Southern European drying (Stahl *et al* 2010, 2012, Gudmundsson *et al* 2017), we identified several regional features highlighting a more nuanced response. Q_{avg}, that includes, for example, signals suggesting increases in Q_{avg} across several basins in the northwestern parts of the Iberian Peninsula, in Italy, and in the Balkans. As many of these basins are also characterized by high-altitude and mountainous headwaters, our results may suggest a dampened response in Southern European basins characterized by snowmelt-driven average discharge conditions. However, that does not hold for low flow conditions that mostly occur in the warm and dry season. Due to an increased likelihood of less accumulated snow and an earlier and more rapid snowmelt (Adam *et al* 2009, Musselman *et al* 2017, Qin *et al* 2020), river flows will not be sustained in the driest periods. In combination with declines in warm season precipitation and increases in evaporative demand (Tramblay *et al* 2020, Tuel and Eltahir 2020), all southern European basins will experience declines in low flows under conditions of 2 K global warming. Drier summer months in combination with more frequent, more intense, and longer drought periods (Forzieri *et al* 2014, Roudier *et al* 2015, Spinoni *et al* 2020) will lead to declines in low flow conditions across western Europe. However, considering annual scales, changes in average discharge conditions are negligible in Western Europe, most likely due to more intense winter precipitation (Jacob *et al* 2018). Towards northeastern Europe and in Alpine regions (with the exception of Southern Sweden), our results show widespread increases in average and low flow statistics that support previous findings and local assessments (Donnelly *et al* 2017, Marx *et al* 2018, Moraga *et al* 2021).

As Europe is one of the most-developed regions across the world and potentially subject to significant socio-economic changes within the coming decades (Flörke *et al* 2013, Wada *et al* 2016), it is of utmost importance to carefully consider changes in water withdrawals when assessing future discharge conditions. Through a systematic alteration of future water withdrawals (in relation to historic water withdrawals, see Methods and appendix C), we were able to assess the sensitivity of mean discharge and low flow statistics to changes in water withdrawals under conditions of 2 K global warming. Our results clearly show that sensitivities are largest (up to parity) across Central Europe which is mainly characterized by heavily managed river systems. The systematic approach of imposing equal relative changes in water withdrawals in all basins also reveals sensitivities propagating downstream, for example, in the Rhine and Seine rivers. However, clear distinctions need to be made between Q_{avg} and the low flow statistics. Low flows are, throughout the study domain and in relative terms, more sensitive to changing water withdrawals (up to parity and up to -4% per 10% for Q_{avg}). However, sustaining sufficient flows under these conditions is particularly important and even small absolute changes (<10 m^3 s^{-1}, resulting in comparably large relative changes) in average and low flow conditions can have severe consequences. Our results clearly point towards (i) the need for a comprehensive representation of water use in hydrological assessments, (ii) the importance of carefully deriving water withdrawal scenarios from socio-economic scenarios (considering changes in population, GDP, technological developments), and (iii) the need to develop and implement sustainable adaptation and water management strategies that account for critical low flow conditions, but (iv) also the potential to mitigate climate change impacts through improving water management in heavily managed basins. Within the identified regions across Central and Western Europe, reduced future water withdrawals of up to 50% can potentially preserve current low flow conditions also under conditions of reduced flows due to 2 K global warming.

However, while we can draw these general conclusions from our results, it is necessary to note that imposing the assumption of fixed relative differences in levels of total water withdrawals across Europe is ad hoc and idealized (and probably too rigid). Actual impacts of water management and policies are and will be more nuanced. Implementing simplified water use scenarios as we have done in this study, neglecting differences related to economic and technological development, likely increases the inherent uncertainties in hydrological and socio-economic impact assessments (Liu *et al* 2017). Nonetheless, we believe that our simplified approach enables a more direct comparison of current water withdrawals under present-day and future conditions and helps in highlighting the importance of considering water withdrawals next to natural flow changes. It also provides a new perspective on current and future water withdrawals and facilitates accessible information on water use impacts under climate change. Yet, controlling water withdrawals requires huge efforts and investments in terms of increasing water use efficiency and water reuse, and enhancing institutional infrastructure and water governance. While we assume certain adaptation and mitigation goals will be met when constraining global warming to 2 K, a reduction of water withdrawals by 50% might be still far-fetched, especially considering the increase in industrial water use under ongoing socio-economic growth, and domestic and irrigation water use under population growth and increasing food and energy demand (Flörke *et al* 2013, Wada *et al* 2016). Required adaptation and water management actions further need to be implemented under the consideration of large uncertainties and financial and institutional challenges that cannot be represented in idealized, single-model hydrological assessments. Nonetheless, our results stress the need for a widespread and immediate transition and/or transformation towards sustainable use of available water resources, even under conditions of substantial methodological and structural uncertainty (Greve *et al* 2018b).

Even though rivers are the major source of freshwater across Europe, regional differences in freshwater abstraction are substantial. Various regions across Europe almost entirely depend on groundwater abstraction, water transfers, or lakes and reservoirs as their main water supply sources. Therefore, from a management perspective, anticipated changes in groundwater supply and recharge, as well as storage and transfer capacities need to be considered and analyzed in more detail. However, we argue that assessing long-term average water supply in terms of only discharge and total runoff already (reasonably) well captures the amount of available and accessible water that supports sustainable water use, thereby providing a reliable first-order assessment of current and future water supply.

The analysis presented in this paper is based on a single hydrological model that is driven by a forcing dataset derived from simulations with a single RCM. The reference simulation with the RCM is driven by a reanalysis dataset implying that it is highly constrained by observed large-scale atmospheric flow. As a consequence, quantitative differences can be expected when using either other hydrological models, forcing datasets derived with other RCMs, or when modifying the PGW assumptions. Concerning the latter, the perturbations for the PGW simulations are based on a 2 K global warming response derived from a 16-member ensemble of simulations of the GCM EC-EARTH (see also appendix B). Using other Coupled Model Intercomparison Project 5 (CMIP5) models will result in differences in the details of the response and in the timing of 2 K global warming. However, by choosing a fixed warming level of 2 K global warming, we do not expect qualitative differences as the deviations in discharge related to the model-specific 2 K global warming signal are comparatively small (see supplementary figure S16 for a comparison of modeled discharge when using either HadGEM2-ES or MPI-ESM-LR warming signals to perturb ERA5). Nonetheless, one should also bear in mind that the PGW-approach only captures changes in the mean climate state, and is, by construction, largely insensitive to the circulation component of climate changes, in particular to variations in long-term variability. For example, potential seasonal shifts in the occurence of low flows under 2 K global warming are not reperesented within PGW experiments (see supplementary figures S17 and S18 highlighting only minimal changes in the seasonal component of low flow occurence).

CWatM is calibrated using observed discharge from hundreds of stations across Europe, showing reasonable performance both concerning average discharge and low flows (see figure 2). However, our simulated results might be sensitive to the choice of other parameter sets or calibration approaches. There is also an additional overrepresentation of observed discharge across Central Europe (see figure 1). Nonetheless, a qualitative reinterpretation of our results (i.e. the high sensitivity of low flows to differences in projected water withdrawals) under any feasible and realistic modification of the model and calibration setup is not expected. In future work the model and calibration setup can be improved for Southern Europe.

5. Concluding remarks

While the impact of changing water withdrawals on relative changes in projected mean discharge is limited, our results show that projected low flows are sensitive to differing water withdrawals under conditions of 2 K global warming. Especially regions of considerable upstream water withdrawals (such as Central Europe) are highly sensitive. We focus on low flows at the 10th percentile (Q_{10}) corresponding to discharge conditions in the driest weeks of the year that best represent hydrological impacts relevant to water managers and end-users. Adapting and mitigating weeks and months of scarcity requires effective measures to preserve and protect existing water sources and strategic (often high-cost) investments such as building large scale reservoirs, implementing efficient irrigation systems, or selecting new crop types or new crop mixtures. Sufficient and reliable water supplies and sustained environmental flows under these conditions are, therefore, particularly critical and challenged by changing climatic conditions and increasing water withdrawals. However, while several studies solely investigated the climate change impact on low flows, our results provide a coupled analysis of conditions under 2 K global warming and their sensitivity to different, idealized water use scenarios. Our results stress the importance of considering future changes in water withdrawals in addition to climate change. Even relatively small changes in water withdrawals (±20%) can lead to differences in projected low flows that exceed the climate change response throughout Central and Western Europe—mainly due to large sensitivities (up to parity) and a negligible climate change response.

The systematic differences in water withdrawals represent the range of possible water use futures from sustainability scenarios suggesting decreases in water withdrawals of up to 50% and business-as-usual scenarios projecting increases in water use even beyond the more conservative estimate of 50% increases applied in this study (Brown *et al* 2013, 2019, Flörke *et al* 2013, Vandecasteele *et al* 2014, Wada *et al* 2016, Boretti and Rosa 2019). Our results show that quantitative assessments of low flows under future warming are impacted by changing future water withdrawals across highly populated and industrialized regions. Therefore, including water withdrawals in hydrological assessments is of utmost importance to communicate the associated broad range of uncertainties. Assessments of climate change impacts in near-natural catchments provide only part of the anticipated response and do not necessarily reflect changes experienced within heavily managed river basins, where climate change assessments for adaptation are needed most. Our results also highlight potentials to manage climate change impacts on river flow, especially within the most critical periods of the year. Regions of substantial low flow sensitivity to water withdrawals will benefit most from coordinated efforts to reduce water withdrawals at regional, national and transnational scales.

Data availability statement

The Community water model (CWatM) is open-source and available at Zenodo (doi: https://zenodo.org/record/3361478) and Github (https://github.com/iiasa/CWatM). The discharge statistics obtained from CWatM simulation results and assessed within this study are available at Zenodo (doi: https://zenodo.org/record/8132868). GRDC data is available at www.bafg.de/GRDC/. HydroBasins data is available at www.hydrosheds.org.

Acknowledgments

This research has received support from the EUCP (European Climate Prediction System) project funded under the European Union under Horizon 2020 (Grant Agreement: 776613) Programme and the SOS-WATER project (Grant Agreement: 101059264) funded under the European Union's Horizon Europe Research and Innovation Programme.

Conflict of interest

The authors declare no competing interests.

Appendix A. Water use in CWatM

In CWatM, water demand is estimated for irrigation, industry and energy, and households. Irrigation water demand estimates account for plant water needs based on soil moisture, seasonal variability, irrigation methods and climatic conditions (Wada *et al* 2014). Using the MIRCA2000 crop calendar (Portmann *et al* 2010) and the extent of irrigated areas (Siebert *et al* 2015), the irrigation water demand is determined at each grid cell. CWatM uses a tiled approach and crop fractions of each grid cell are further distinguished into paddy and non-paddy cultivation. Irrigation water demand and associated water withdrawals are computed separately for paddy irrigation and non-paddy irrigation. Paddy cultivation represents flooding irrigation. CWatM represents flooded paddy fields by applying a 50 mm surface water depth in a period close to the harvest. The respective change of that surface water layer after considering infiltration to lower soil layers, open water evaporation, and precipitation determine the irrigation water demand for paddy fields. For non-paddy cultivation, soil moisture in the upper two soil layers is used to determine irrigation demand as the difference between field capacity of the soil layers and actual soil water. Based on the determined irrigation demand, actual water withdrawals are calculated using a water efficiency rate.

Estimating industrial water demand is based on gridded, historical industrial water demand data and water use intensity time series which are a function of Gross Domestic Product (GDP), electricity production, energy consumption, household consumption, and a technological development rate per country (Burek *et al* 2020). Domestic/household water demand is downscaled based on population per grid cell multiplied with a country-specific per capita domestic water withdrawal rate. Domestic water demand is further adjusted based on temperature and country specific estimates of economic and technological development.

Actual water withdrawals have been extensively validated (Wada *et al* 2014) and are estimated based on water demand and available water resources. Water demand can be met by both available surface water resources and groundwater, and is abstracted in the following order from the following sources: (i) renewable groundwater resources, (ii) surface water in rivers, reservoirs and lakes, and (iii) non-renewable groundwater resources. Water can also be sourced from neighboring downstream grid cells depending on the drainage network (up to five grid cells downstream). Due to sourcing from downstream grid cells and from non-renewable groundwater in case of depleted renewable groundwater and surface water resources, the water demand is always met in CWatM and actual withdrawals are equal to the total water demand. CWatM further accounts for return flows, and conveyance and application losses.

In CWatM, reservoir operations are parameterized. The model strives to maintain a consistent outflow rate as much as possible. Retention effects due to reservoirs and lakes larger than 5 km^2 are coupled to the routing routine in CWatM, whereas reservoirs and lakes smaller than 5 km^2 are part of the runoff generation module. Reservoir operations in CWatM maintain a minimum storage capacity of 10% and a maximum storage capacity of 90% of the total reservoir storage capacity. CWatM considers a minimum outflow of 20% of the average discharge to retain ecological flows. The maximum (non-damaging) outflow is set to 400% of the average discharge. In between, reservoir outflow is parameterized to deliver steady outflow rates as close to the average discharge as possible while accounting for reservoir fill fraction. Please refer to the model description for more detailed information on water demand calculation, associated water withdrawals, and reservoir operations in CWatM (Burek *et al* 2020).

Appendix B. Forcing data

The climate forcing is provided by a set of PGW experiments (Prein *et al* 2016, Brogli *et al* 2018, Aalbers *et al* 2023) covering the simulation period 1981–2010. These simulations are based on the RACMO RCM (Meijgaard *et al* 2012) at 0.11° spatial resolution within a western European domain (see figures 1 and S3). The spatial resolution and model setup correspond to the standards used within EURO-CORDEX experiments (Kotlarski *et al* 2014, Prein *et al* 2015) and the forcing data have been remapped to the native 5′ resolution of CWatM using bilinear interpolation. In the reference experiment, RACMO is forced at the lateral and sea surface boundaries of the model domain by unperturbed ERA5 reanalysis data (Hersbach *et al* 2020), while in the PGW experiment, the forcing data consist of perturbed reanalysis data. Perturbations are added to the ERA5 reference data corresponding to climate change patterns of surface pressure and sea surface temperature, and atmospheric profiles of temperature, relative humidity, and wind speed components that are retrieved from a 16-member single model initial condition ensemble of EC-EARTH (Hazeleger *et al* 2011) global climate simulations. The perturbations are determined as the ensemble mean difference between 30-year mean atmospheric and sea surface states between a future period (2048–2077) and a reference period (1991–2020) corresponding to 2 K global warming in the EC-EARTH transient simulation under external forcings according to the Representative Concentration Pathway 8.5 (RCP8.5) emission scenario. Please note that global warming in the 1991–2020 period is already at 0.9 K compared to the 1850–1900 pre-industrial period. The results presented here are, therefore, considering the impact of an additional 2 K global warming. By construction, the two forcing data sets are primarily different in their mean climate state with 2 K global warming. That includes, e.g. higher temperatures in the perturbed forcing data, enhanced stratification of mean temperature vertical profiles, larger atmospheric vapor contents corresponding to the higher temperatures, but generally slightly lower relative humidity over land, in summer. Both experiments are quite similar in their day-to-day, large-scale circulation as enforced by ERA5. The PGW approach with the same set of RACMO experiments as described here has also been applied in a recent study of drought episodes in the western European domain (Aalbers *et al* 2023). Please refer to supplementary figure 3 for more details on the forcing data.

Appendix C. Incremental adjustment of water withdrawals

We have performed 11 hydrological simulations adjusting the water demand as follows: Internally, CWatM estimates industrial and domestic water demand (see appendix A) as a single number for each grid cell. That number is multiplied by the respective factor $(0.5, 0.6, 0.7, \ldots, 1.5)$ to obtain adjusted industrial and domestic water demand in the range between ±50%. The adjusted industrial and domestic water demand will be used to estimate water withdrawals. Irrigation demand depends on available soil water and is potentially different under PGW conditions due to climate-driven changes in soil moisture. However, to enable a direct comparison to adjusted domestic and industrial withdrawals, we also apply the percentage difference in relation to irrigation withdrawals under historic conditions. That means we take the historic irrigation water withdrawals as reference and adjust irrigation efficiency under PGW conditions such that the adjusted irrigation water withdrawals represent the ±50% range. That approach ensures that we do not change soil water conditions and, as a consequence, irrigation demand itself. Adjusting efficiency also ensures that we apply the required irrigation water demand even under conditions of reduced irrigation water withdrawals. Please note that by adjusting water withdrawals and irrigation efficiency, we effectively also alter return flows.

Appendix D. Calibration and validation

Calibration has been performed independent from the analysis presented in this study using the WFDEI dataset. A set of 12 model parameters has been calibrated against 363 daily discharge time series from the GRDC within the larger EURO-Cordex domain. The selection of stations has been used in previous studies (Zhao *et al* 2017, Burek *et al* 2020) and is based on a global dataset of observed daily discharge from the GRDC (Koblenz, Germany) and (a) a minimum of five-year consecutive coverage during the period 1981–2010, (b) a minimum catchment size of 9000 km^2, (c) and based on stations with no more than 30% difference in the upstream area from the reported upstream area and upstream area based on the river network. We refined this selection by using a minimum catchment size of 2000 km^2 and a minimum of five-year coverage between 1990–1999 (that is because, in that period, most GRDC data are available), which results in a total of 363 stations. Even though more stations are available across Europe (and especially Southern Europe), most data records are either too short or include frequent missing days. Such records do not fulfill our requirements and are therefore not considered.

For this study, we did not use a full calibration for each of the 363 stations. Instead, we used the sum of a modified version of the Kling-Gupta Efficiency (KGE) (Kling *et al* 2012) across all stations as the objective function following previous approaches (Burek *et al* 2020, Greve *et al* 2020). That finally results in one parameter set across the entire domain. The modified version of the KGE' is given as:

$$\text{KGE'} = 1 - \sqrt{(r-1)^2 + (\beta-1)^2 + (\gamma-1)^2} \quad (1)$$

The value r denotes the correlation coefficient between simulated and observed discharge, $\beta = \mu_s/\mu_o$ represents the bias ratio between mean, simulated (μ_s) and observed discharge (μ_o). The ratio $\gamma = CV_s/CV_o$ quantifies the variability ratio between the simulated (CV_s) and observed (CV_o) coefficient of variation. Please note that the unmodified KGE is computed based on the standard deviation instead of the coefficient of variation. It is important to note that the three addends r, β and γ have their optimum at unity. The KGE' can be interpreted as the Euclidean distance from the optimal value (i.e. unity) of the Pareto front and provides an estimate that represents maximum correlation, and minimum mean bias and variability.

Calibration is performed using an evolutionary computation framework in Python called DEAP (Fortin *et al* 2012). As objective function for each station we used the KGE' to compare observed with simulated daily discharge for the time period 1 January 1990–31 December 1999. The calibration uses a population size (μ) of 256 and a recombination pool size (λ) of 32. The number of generations was set to 20, which we found was sufficient to achieve convergence for stations.

The sum of KGE Efficiency of 363 stations for each parameter set is calculated by classifying the station KGE into five classes ($\geqslant 0.5, \geqslant 0.6, \geqslant 0.7, \geqslant 0.8, \geqslant 0.9$) and multiplying the number of stations in each class with a weighting factor $(2, 3, 4, 5, 6)$. The parameter set obtaining the highest total sum based on this procedure has been selected. The calibrated parameter set, therefore, represents model settings optimizing discharge across the entire set of observations rather than providing (i) specific parameter sets for individual catchments, or (ii) default ad-hoc parameter sets.

Please refer to supplementary table S2 for an overview of all parameters and their respective calibration ranges. The calibration ranges are defined to represent a realistic hydrological response associated with the alteration of the parameter value.

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