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Deliverable D4.2

Climate/non-climate attribution of hydro-meteorological events and losses

Deliverable Title	*Climate/non-climate attribution of hydro-meteorological events and losses*
Brief Description	*Using indicators for (cross-) sectoral climate impacts, attribution of hydro-meteorological events and impacts will be developed as a service. In order to better understand the*

	underlying mechanisms of climate impacts, assessments will be performed for both climate and non-climatic drivers at various spatial scales. To analyse non-climate drivers, we will use the socio-economic data from the IIASA's Water Futures and Solutions Initiative. A key component of the WFaS analysis is the assessment of human water management that help to understand the extent of water resources challenges consistently with the community-developed SSPs and newly adopted SDG.		
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1. Executive summary

This report will summarize the progress made concerning the application of a large-scale hydrological model (the Community Water Model, CWatM) that enables impact assessments considering water use under historical conditions and based on different socio-economic scenarios. The model will be utilized on a 5’ (ca. 9x9km) spatial and daily temporal resolution across Europe. This enables the generation of a set of experiments assessing both pristine, natural (i.e., no water demand modelling) and water use conditions (including water demand) under climate change and their impact on hydrological extreme events. CWatM was forced by two sets of high-resolution regional climate model datasets widely used and partly generated within EUCP: (i) an ensemble of 20 regional historical and future climate simulations based on different regional climate models subject to a set of global climate models determining the associated boundary conditions, as well as (ii) pseudo-global warming experiments using a regional climate model in a European domain subject to reanalysis-based boundary conditions under (a) reference and (b) 2K-global warming conditions. The set of experiments enables the assessment of impacts of historical and projected water demand on hydrological extremes compared to natural conditions, as well as the potential impact of historical water use under conditions of 2deg global warming.

The results show that current and projected water use largely increases the risk of low flows and hydrological drought across most parts of Europe, widely doubling low flow occurrences. Strongest impacts are found in the Mediterranean region, with low flows decreasing by 30% to 50%. In addition, anticipated climate change widely exacerbates low flow probabilities and mean annual lowest flows in southern Europe. The research presented in this report highlights the importance of accounting for the significant impact of human water use on hydrological extremes, which is often neglected in hydrological impact assessments.

2. Project objectives

These deliverables have contributed to the following EUCP objectives (Description of Action, Section 1.1):

No.	Objective	Yes	No
1	Develop an ensembles climate prediction system based on high-resolution climate models for the European region for the near-term (~1-40 years)		x
2	Use the climate prediction system to produce consistent, authoritative and actionable climate information	x	
3	Demonstrate the value of this climate prediction system through high impact extreme weather events in the near past and near future	x	
4	Develop, and publish, methodologies, good practice and guidance for producing and using EUCP’s authoritative climate predictions for 1-40 year timescales	(x)	

3. Detailed report

3.1. Objectives of this report

The main objectives of this report are **(i) to introduce the large-scale hydrological and water resources Community Water Model (CWatM**), a global hydrological model developed at IIASA partly within this project. **(ii) Using CWatM to assess both climatic and non-climatic drivers contributing to current and projected hydrological extremes** by using (a) an ensemble of near- to mid-term regional climate projections also utilized within WP2 and WP3 of this project, as well as (b) reanalysis-driven pseudo-global warming experiments provided by WP2 project partner KNMI.

3.2. Development of a large-scale hydrological and water resources model

3.2.1 Introduction

At the present day, the distribution of surface water and the availability of groundwater resources is heavily impacted by human water use and interventions. Considering an ever-growing population, leading to increasing food, energy and production demands relying on sufficient water resources, results in widespread impacts on the supply of water. By additionally considering potential water shortages (or excess) arising from recent and anticipated climate change, a reliable water supply is largely at risk in regions with large water demand as well as regions likely to experience drying climatic conditions. The nexus of water-climate-human interactions calls for more holistic approaches considering both climatic and socio-economic pressures to assess their distinct as well as combined impact on the availability and accessibility of water resources, and on the occurrence and intensity of hydrological extremes, such as floods and droughts.

Within the past decade, interactions between natural water systems (such as rivers, lakes, groundwater, etc.), climate change (both historic and projected), and socioeconomic impacts, including water and ecosystem management, have increasingly been incorporated into large-scale to global hydrological models (Wada et al., 2017). The range of models including these processes is growing and comprises, e.g., WaterGAP (Alcamo et al., 2003; Flörke et al., 2013), H08 (Hanasaki et al., 2008, 2018), and PCR-GLOBWB (Van Beek et al., 2011; Wada et al., 2014). In comparison to more traditional, catchment-scale hydrological models, these models are designed at grid cell level and can be used to assess large-scale historic and projected changes in hydrological characteristics and water resources forced by either observations-based (such as, e.g., reanalysis data) as well as projected climate model data. To assess large-scale changes in hydrological conditions in a changing world, the incorporation of human interventions is becoming essential for the realistic simulation of global and regional hydrological processes. In particular, simulations of human water demand from different sectors such as agriculture, industry, and domestic could have a large impact on estimated hydrological storage and flows (Alcamo et al., 2007; Wada et al., 2016). Additionally, more efforts have gone into better groundwater representation in large-scale hydrological models to realistically simulate groundwater levels and surface–groundwater interactions (Pokhrel et al., 2015; Wada, 2016; de Graaf et al., 2017).

In comparison to the large number of highly specialized and parameterized catchment-based models, gridded, large-scale hydrological models still remain a niche within the hydrological community. Promoting the use of these models and increasing their accessibility is the main motivation for the development of CWatM, as the model aims to overcome this barrier by implementing an open-source, modular modeling approach covering regional to global scales. The development team especially acknowledges the necessity to create a community-driven modeling environment that facilitates the exchange of ideas, components or modules, data, and results in an easily communicable format. A user-friendly and flexible model structure will enable more active engagement with stakeholders and associated capacity training.

3.2.2. The Community Water model

CWatM is a hydrological rainfall-runoff and channel routing model developed at IIASA within the past years (Burek et al., 2020). It is process-based and used to quantify water availability, human water use and the effects of water infrastructure, including reservoirs, groundwater and irrigation. 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). However, given different input data, the model can be set up at any resolution ranging from kilometre-scales up to coarse climate-model specific resolutions. It operates at daily time steps (with sub-daily time stepping for soil and river routing). A schematic view of all featured processes is provided in Fig. 1.

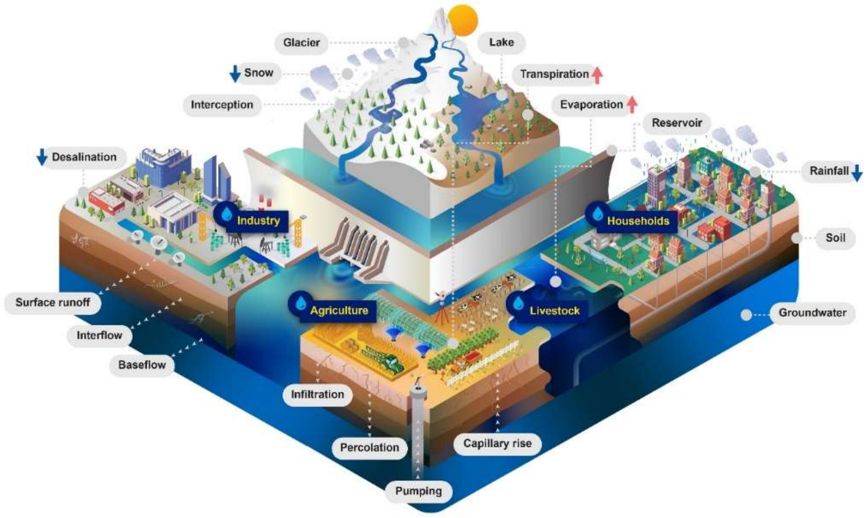

Figure 1: Schematic illustration of the key processes included in CWatM. In natural mode, CWatM features several important land surface and terrestrial hydrological processes, related to the modelling of river flow, surface and subsurface runoff, groundwater, soil moisture, snow, lakes, and evaporation. By considering human water use and water demand, several modules in CWatM represent processes related to irrigation, industrial, domestic and livestock water demand, groundwater abstraction, reservoirs, and dams.

As forcing data, the model requires daily estimates of precipitation, as well as surface air temperature, wind speed, relative humidity, incoming long- and shortwave radiation, and surface air pressure as inputs to calculate potential evaporation. These variables are among the standard output of state-of-the-art Earth system and climate models, as well as observation-based forcing and reanalysis datasets. However, bias correction might be necessary. In the default version, potential evaporation is computed based on the reference-crop FAO56 Penman-Monteith parameterization, but the choice of other options is possible. CWatM uses a range of available and established data sets to implement elevation data, soil properties, crop factors and calendars, lakes, and reservoirs. Runoff, drainage, and routing are estimated based on established methodological approaches. The source code is available at Zenodo and Github (https://github.com/CWatM).

CWatM is comparable to other state-of-the-art GHMs (Burek et al., 2020), such as H08 (Hanasaki et al., 2008), WaterGAP (Alcamo et al., 2003), PCR-GLOBWB (van Beek et al., 2011; Wada et al., 2014), and LPJmL (Bondeau et al, 2007). However, the main novelty of CWatM does not lie in the development of entirely new concepts for modeling hydrological and socioeconomic processes but in combining existing good practice in various scientific communities beyond hydrology itself. One of the main advantages of CWatM is a modular model structure which is open source and uses state-of-the-art data storage protocols as input and output data. The online user manual (https://cwatm.iiasa.ac.at/) and automatic source code documentation make CWatM an easy-to-use tool which can be integrated and coupled to other toolsets such as land use modeling and hydro-economic modeling. CWatM also strives to build up a community which can freely use an open-source hydrological model with the possibilities of coupling it to other water management models such as WEAP (Yates et al., 2005) and ECHO (Kahil et al., 2018), as well as linkages to other sectoral models (e.g., land use, agriculture, etc.). Within IIASA, existing linkages to state-of-the-art models for energy (MESSAGE) (Sullivan et al., 2013), land use and ecosystems (GLOBIOM) (Havlík et al., 2013), agriculture (IIASA-EPIC) (Balkovič et al., 2014), water quality (MARINA) (Strokal et al., 2016), and the hydro-economy (ECHO) (Kahil et al., 2018) have been established. The goal is to implement and promote an open-source platform as a way to exchange ideas and develop model codes that facilitate capacity enhancement, especially in regions with limited access to high-performance computing facilities and high-resolution data. In this context, scalability is an important feature enabling the use of the model at the regional-to-catchment scale, and also at the continental-to-global scale, which facilitates learning between global and regional hydrological model applications.

From a software perspective, CWatM includes the following features: (i) CWatM is implemented as an open-source modular structured Python program for easy comprehension of the code and to facilitate extensibility, (ii) CWatM is designed for multiplatform use to adjust the model to the users' needs and capacity, (iii) CWatM features a high level of modularity to increase extensibility. For example, regarding the implementation of different methods to estimate potential evaporation, various water demand schemes, the representation of the water-food nexus, for flood forecasting, links to hydro-economic modeling, etc., and (iv) CWatM includes a state-of-the-art data structure for reading and writing spatiotemporal data to allow for efficient management of data storage and facilitate the development toward high-resolution models. The modular structure of the model enables high flexibility regarding experiment design. In the following, we use two versions of CWatM: (i) the pristine, natural mode, switching off any water demand calculations (i.e., no water demand, no land use change, no reservoirs), and (ii) the full set of modules including water demand calculations. In comparison, these experiments enable the assessment of water use impacts on current and projected hydrological extremes.

It has been shown that streamflow conditions are subject to human disturbances (Vicento-Serrano et al., 2017; Vicento-Serrano et al., 2019). However, water use has often not been considered in previous modelling assessments of recent and projected hydrological extremes across Europe. Hence, as the addition of water use in CWatM (and other global hydrological models, see .e.g, Burek et al., 2020) leads to improved performance regarding streamflow statistics in comparison to observed discharge, the goal of this report is to highlight the importance of considering water use in regional to continental hydrological modelling experiments.

3.3. Climatic vs. non-climatic drivers of hydrological extremes

3.3.1 Introduction

The availability of water resources is at risk both by changes to the water cycle under conditions of ongoing climate change, as well as due to increasing water demand as a consequence of growing populations and socio-economic development (Wada et al., 2013, 2014, 2016; Flörke et al., 2013). If the water demand exceeds ca. 40% of the available water resources, water scarcity is prevalent and water shortages can occur, especially during periods of intense/frequent droughts. Under these conditions, water demand is often met through water extractions at the expense of environmental flows and water-dependent ecosystems or through increasing abstraction of non-renewable groundwater resources. Projected increases in mean water scarcity thus pose significant challenges to societies, economies, and ecosystems. However, required adaptation and water management actions need to be implemented under conditions of large uncertainties and structural and governmental challenges, calling for a widespread and immediate transition and/or transformation towards a sustainable use of available water resources (Greve et al., 2018a).

In Europe, historic changes in local runoff, river stream flow, and water availability follow a distinct pattern of observed increases in northern Europe and decreases in southern Europe (Stahl et al., 2010, 2012). This pattern is clearly attributable to anthropogenic climate change and will likely intensify under conditions of ongoing climate change (Gudmundsson et al., 2017). However, changes in average streamflow (Vicente-Serrano et al., 2019) and, in particular, regarding low flows/droughts (Vicento-Serrano et al., 2017) in parts of southern and western Europe are largely also explained by human disturbances, such as agricultural and irrigation intensification and land use changes.

Assessments of observed streamflow records show a mixed response of river flood magnitude and frequency to historic and recent climate change across Europe (Blöschl et al., 2019), However, the evident pattern of increases in northern vs. decreases in southern Europe is still detected. By not considering human water use, high flows and annual peak discharge are, within the 21st century, projected to further decrease in southern Europe, with only little changes detected in northern Europe (Thober et al., 2018). However, it needs to be noted that anticipated changes in river flooding remain highly uncertain apart from the evident pattern of northern European wetting and southern European drying (Thober et al., 2018; Gudmundsson et el., 2017, Greve et al., 2018b). The climate change response of low flows/hydrological drought is indeed more robust and significant decreases are projected in southern Europe within the next decade (Prudhomme et al., 2014; Forzieri et al., 2014). However, also parts of western and central Europe are likely to experience more intense and frequent droughts under high climate change conditions (Prudhomme et al., 2014). In addition, taking into account human water use can lead to an additional increase of up to 30% across Europe (Forzieri et al., 2014).

The observed impact of human water use and water management highlights the need for considering human water use in streamflow assessments, both regarding mean changes and changes in hydrological extremes. So far, only few modelling studies assess the projected impact of historical and projected water use on changes in hydrological extremes (e.g., Forzieri et al., 2014). However, given the broad and extensive use of water resources, it is of utmost importance to systematically assess regional impacts on floods, high flows, low flows, and, in particular, drought in upcoming climate change assessment (van Loon et al., 2016)

In this report, the recently developed CWatM is forced by a set of regional climate model simulations, used within EUCP, to assess near- to mid-term impacts on hydrological extremes by singling out the response attributable to historic and projected water demand and climate change.

3.3.2 Experimental Setup

For the purpose of this report and IIASA's activities within EUCP, CWatM is used to assess the impact of non-climatic and climatic drivers of hydrological extremes by simulating discharge in a set of experiments considering climate change and human water use. CWatM provides the flexibility to simulate both natural and water demand conditions, i.e., by using regional climate change simulations, it is possible to isolate the climate and water demand impact on discharge extremes. Therefore, CWatM is set up at the default 5' high resolution within a European domain covering all major river basins in southern, western, northern and central Europe (see Fig. 2).

<u>Forcing data:</u> Two different forcing datasets are used:

Regional climate model (RCM)	Climate model (GCM)
CLMcom-CCLM4-8-17	• CNRM-CERFACS-CNRM-CM5 • MOHC-HadGEM2-ES • MPI-ESM-LR
CLMcom-ETH-COSMO-crCLIM-v1-1	• MPI-ESM-LR • NCC-NorESM1-M
DMI-HIRHAM5	• ICHEC-EC-EARTH • MPI-ESM-LR
IPSL-WRF381P	• IPSL-IPSL-CM5A-MR • MOHC-HadGEM2-ES • NCC-NorESM1-M
KNMI-RACMO22E	• ICHEC-EC-EARTH • IPSL-IPSL-CM5A-MR • MPI-ESM-LR • NCC-NorESM1-M
SMHI-RCA4	• CNRM-CERFACS-CNRM-CM5 • ICHEC-EC-EARTH • IPSL-IPSL-CM5A-MR • MOHC-HadGEM2-ES • NCC-NorESM1-M

Table 1: Regional climate models and their associated large-scale climate forcing.

(i) **EURO-CORDEX:** A 20-member multi-model ensemble of EURO-CORDEX regional climate simulations covering the period from 1961 to 2100 at 0.11° spatial resolution. We use daily output of the above-mentioned variables (see Sec. 3.2.2.) within this period to force CWatM. The European-Coordinated Downscaling Experiment (EURO-CORDEX, Jacob et al., 2020), as part of the World Climate Research Program (WCRP) CORDEX initiative, coordinates the regional climate modelling activities of various research groups and institutes. The regional climate models are itself forced by a set of global climate models from the Coupled Model Intercomparison Project 5 (CMIP5, see Table 1). The period from 1961 to 2005 thus corresponds to the historical period of the associated CMIP5 data. From 2006 to 2100, CMIP5 simulations are based on the high climate change scenario under the Representative Concentration Pathway 8.5 (RCP8.5). The

EURO-CORDEX domain covers most of Europe, however, some of the major eastern European river basins (e.g., the Volga river) are not entirely covered by the EURO-CORDEX domain and are exempt from this analysis (see Fig. 2). EURO-CORDEX is also used for various other activities within EUCP.

(ii) **KNMI-PGW:** A set of pseudo-global warming experiments (Prein et al., 2017; Brogli et al., 2019) covering the period from 1979-2010 provided by the EUCP member institution KNMI and generated and used within WP2. These simulations are based on the RACMO regional climate model (that is also part of the EURO-CORDEX ensemble) at 0.11° spatial resolution covering a smaller subdomain of the EURO-CORDEX domain (see Fig. 2). In the reference experiment (i) RACMO is forced by unperturbed ERA5 reanalysis data, while in the pseudo-global warming experiment (ii) the forcing data consist of perturbed reanalysis data. Perturbations added to ERA5 correspond to climate change patterns retrieved from a 16-member ensemble of EC-EARTH (a CMIP5 climate model) global climate simulations under conditions of 2K global warming. By construction the two forcing data sets are primarily different in their thermodynamics consistent with 2K global warming (higher temperatures in the perturbed forcing data; enhanced stratification of mean temperature vertical profiles; larger atmospheric vapour contents corresponding to the higher temperatures, but generally slightly lower relative humidity), while they are quite similar in their day-to-day large-scale circulation as enforced by ERA5.

Figure 2: Major basins (light blue) within the EU-Cordex domain. Please note that major eastern Europe basins are not fully within the domain of the EU-Cordex forcing data and are excluded from the modelling setup. The domain indicated by dashed lines correspond to the smaller KNMI-PGW domain. A set of 20 gauging stations (position as indicated by grey dots) within medium to large basins (dark blue) across Europe is chosen to illustrate impacts at catchment level in more detail

Experiments: CWatM is used (i) under pristine, natural conditions with no representation of water demand, and (ii) under conditions considering water demand from the agricultural, industrial and household sector. Thus, for both the EURO-CORDEX ensemble and the KNMI-PGW data, a set of four experiments is generated, enabling the comparison of water demand and climate change conditions:

Experiment	Climate change	Water demand
nat-ref	-	-
dem-ref	-	+
nat-fut	+	-
dem-fut	+	+

(nat-ref) Reference model runs under natural and historical climatic conditions. For EURO-CORDEX, this covers the reference period 1980-1999. For KNMI-PGW, this covers 1981-2010 under reference ERA5 conditions.

(dem-ref) Model runs including water demand calculations under historical conditions (both historical climatic and water use conditions, Fig. 3). The considered periods are similar to nat-ref.

(nat-fut) Model runs under natural and projected climate change conditions. For EURO-CORDEX, the near- to mid-term future period is 2040-2059 (covering a range between 1.5K and 2K global warming). For KNMI-PGW, this covers 1981-2010 under perturbed ERA5 conditions.

(dem-fut) Model runs including water demand calculations under projected climate change conditions. The considered periods are similar to nat-fut. For EURO-CORDEX, water demand conditions are estimated based on the Shared Socioeconomic Scenario 2 (SSP2, O'Neill et al., 2014), also used within IIASA's Water Futures and Solutions Initiative (WFaS, Wada et al., 2016). For KNMI-PGW, historical water use (1981-2010) was assessed under climate change conditions.

The outlined set of experiments enables assessments singling out the climate change response (nat-fut), as well as impacts by human water use (dem-ref).

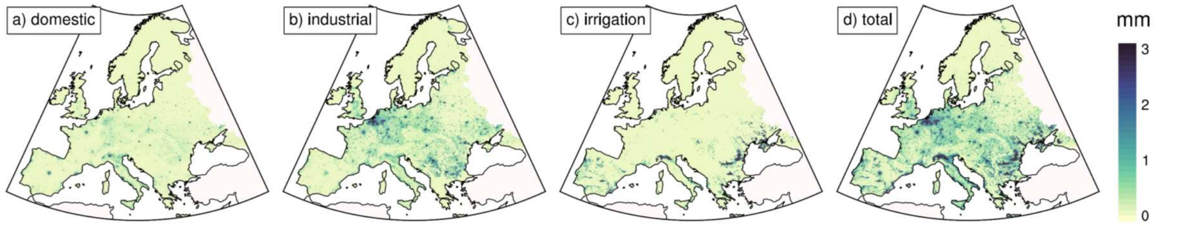

Figure 3: Sectoral and total yearly water consumption as modelled by CWatM under dem-ref using the EURO-CORDEX ensemble. CWatM separates between a) domestic, b) industrial, and c) irrigation water demand

Calibration: The hydrological impact simulations are generated using a calibrated version of CWatM. A set of model parameters representing, e.g., snow melt, soil, and routing characteristics, have been calibrated against 363 discharge time series from gauging stations across Europe. In comparison to observed discharge, CWatM shows slight biases within the range of +/- 20% in mean discharge, as well as in the 5th and 95th percentile

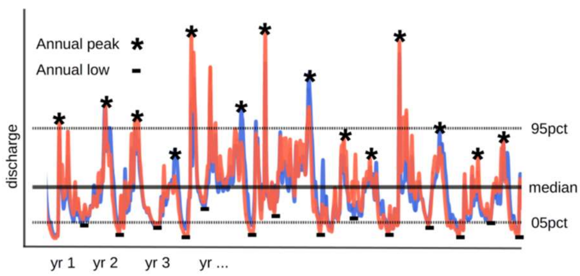

Figure 4: Illustrative example of discharge statistics for a generic discharge time series

(low and high flows) in the majority of basins (not shown here). A slight wet bias is primarily located in central and northern Europe, while there is a tendency towards a dry bias in northern Europe.

Discharge statistics: Hydrological extremes are here assessed in terms of annual peak daily discharge and annual peak (lowest) daily low flow. We further assess low and high flows defined as the 5th and 95th percentile of the daily discharge distribution of all years (Fig. 4).

3.3.3. European ensemble of hydrological impact simulations and projection

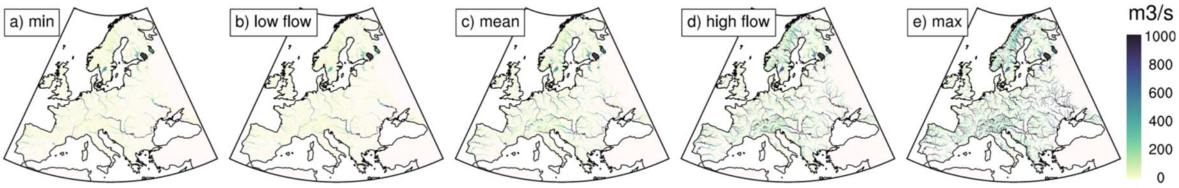

Figure 5: : Ensemble daily discharge statistics based on the set of EU-Cordex forcing data within the historic period (1980-99) under nat-ref: (a) Average annual peak (lowest) low flow, (b) low flows representing the 5th percentile, (c) mean daily discharge, (d) high flows representing the 95th percentile, and (e) average annual peak discharge.

Based on the full EURO-CORDEX ensemble provided as forcing to CWatM, ensemble-mean statistics for natural conditions in the reference period (1980-99, nat-ref) are shown in Fig. 5. Mean daily discharge tops well above 1000m^3/s in most of the major European river basins, with highest discharge values reached in the Danube basin. Average annual daily peak low flows and low flows (5th percentile) are considerably smaller, with few southern European basins at risk to run completely dry under conditions of prolonged drought. Nonetheless, peak discharge in all major basins across Europe reaches values well above 1000m^3/s. Comparing peak low and high discharge under nat-ref to the other experiments, reveals a number of important insights on the impact of human water use and climate change on annual peak hydrological extremes across Europe (Fig. 6). Under dem-ref, i.e., by adding human water use, considerable decreases in annual peak low flows

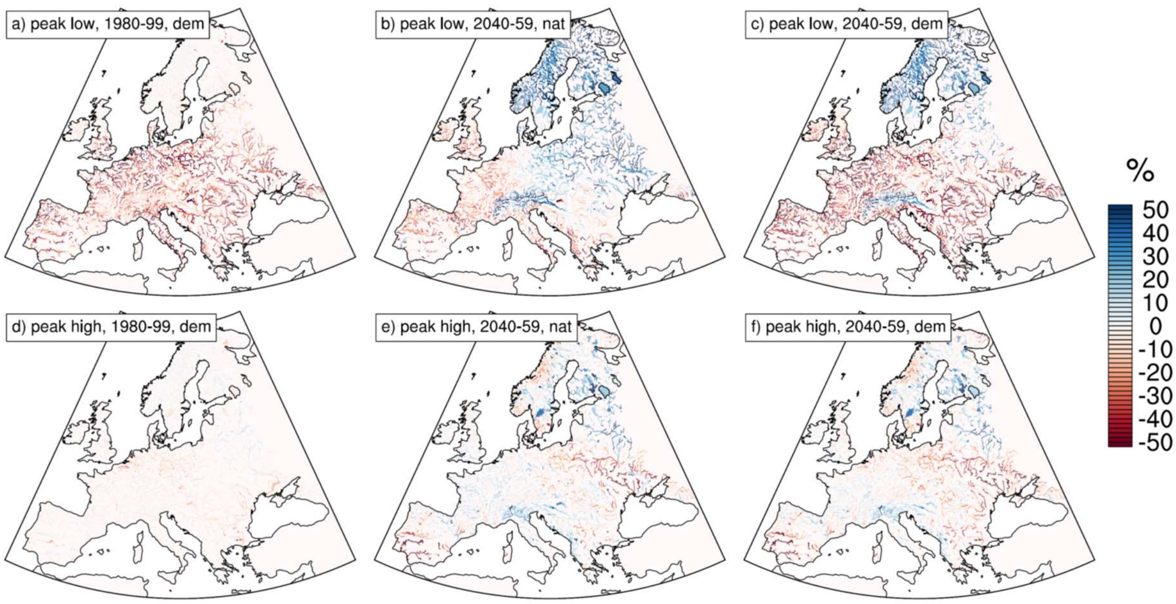

Figure 6: Relative difference (in percent) in ensemble-average annual peak low flows (upper row) and annual peak discharge (bottom row) between nat-ref and (a,d) dem-ref in the historic period (1980-99), (b,e) nat-fut in the future period (2040-59), and (c,f) dem-fut in the future period (2040-59). The left column (a,d) illustrates the impact from human water use on peak flows, whereas the middle column (b,e) illustrates the climate change impact. The combined impact is shown in the right column (c,f).

are found across southern and central Europe, with largest decreases in most of the heavily managed central European basins (see also Fig. 3). For peak low flows under nat-fut, i.e., by adding a climate change response, the common pattern of decreases in southern Europe vs. increases in northern Europe is evident. However, the gradient is shown to be strongest from southwestern Europe towards north-eastern Europe, with Alpine regions experiencing considerable increases in peak low flows as well. The combined response in peak low flows (dem-fut) shows an amplified drying in most parts of southern and central Europe (drying in dem-ref plus drying in nat-fut). Increases in peak low flows in the combined response are only found in Scandinavia and the Alps. It needs to be noted here that the climate change response is surprisingly linear, i.e., differences between nat-ref and nat-fut are roughly identical to differences between dem-ref and dem-fut (not shown). Slight regional differences will be assessed in future assessments.

Peak (high) discharge under dem-ref only shows no to small negative changes. The relative climate response in peak discharge (nat-fut) is also weaker in comparison to the response in peak low flows (even though absolute values might still be considerable). Under nat-fut and dem-fut, slight decreases in peak discharge are found in parts of southwestern Europe (Iberian Peninsula) and eastern Europe (particularly in Ukrainian basins). Increases are located in southern Alpine catchments and in parts of eastern Scandinavia. Considering differences in low/high flows (Fig. 7) reveals similar patterns. However, the overall response in high flows is weaker in comparison to annual daily peak discharge.

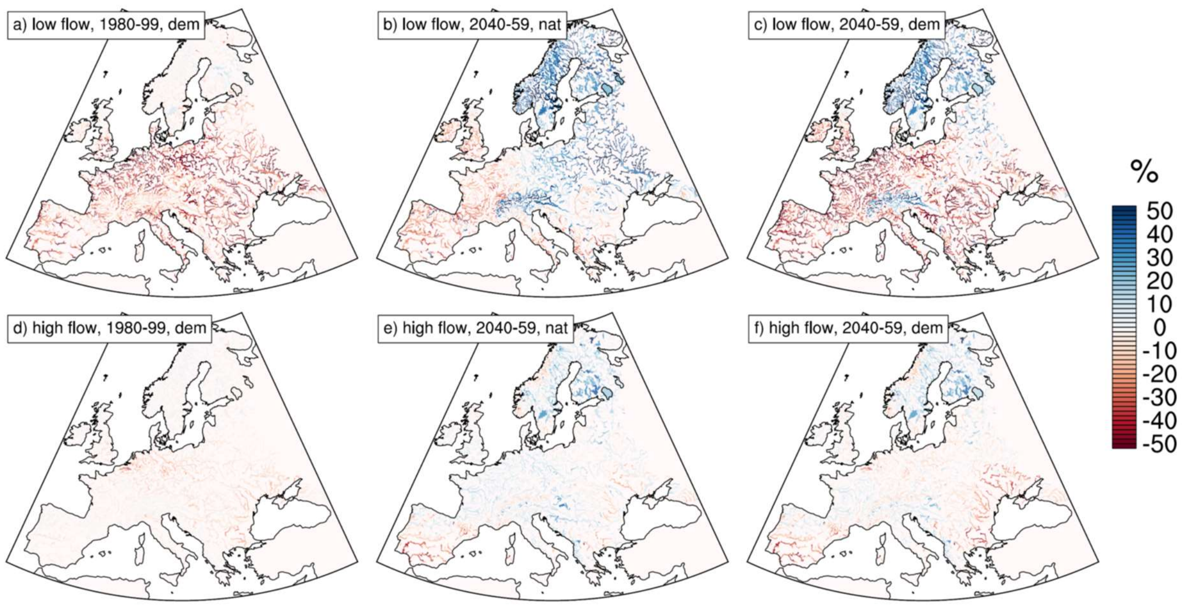

Figure 7: Relative difference (in percent) in ensemble-average annual low flows (upper row) and high flows (bottom row) between nat-ref and (a,d) dem-ref in the historic period (1980-99), (b,e) nat-fut in the future period (2040-59), and (c,f) dem-fut in the future period (2040-59). The left column (a,d) illustrates the impact from human water use on low/high flows, whereas the middle column (b,e) illustrates the climate change impact. The combined impact is shown in the right column (c,f).

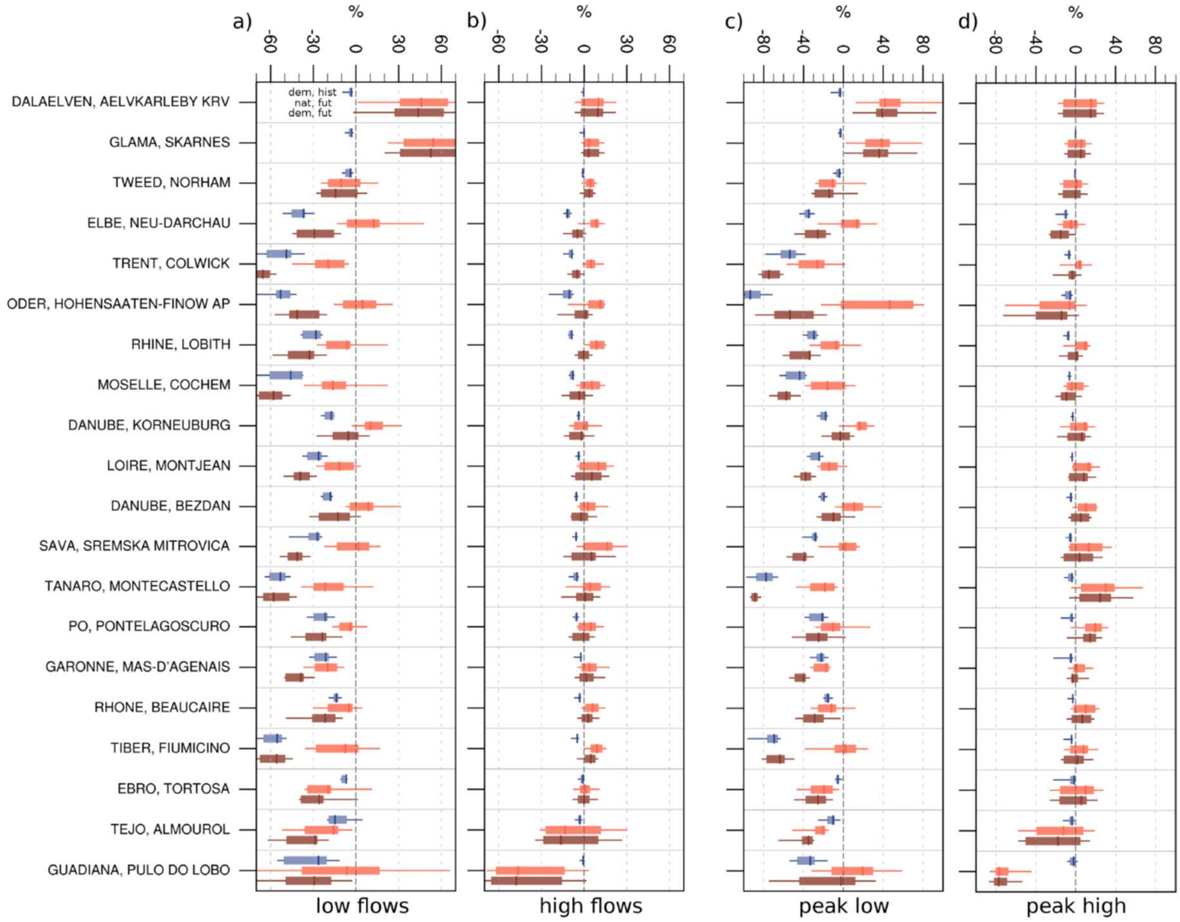

Figure 8: Relative difference (in percent) in average annual a) low flows, b) high flows, c) peak low flows, and d) peak discharge for the full set of EU-Cordex forcing models in the selected basins. Differences relative to nat-ref are estimated for nat-dem in the historic period (blue, 1980-99), nat-fut in the future period (light red, 2040-59), and dem-fut in the future period (dark red, 2040-59). The boxes (horizontal lines) indicate the interquartile (full) range of relative differences from the set EU-Cordex forcing models. The center line in each box denotes the median response.

A closer look at the differences between the experiments for the selected basins (see Fig. 2) enables an assessment of the underlying uncertainty. Fig. 8 highlights the uncertainty originating from the 20-member EURO-CORDEX ensemble and further underlines the results found at domain-level. Regarding low flows and annual peak low flows, the (near-natural) Scandinavian catchments (Dalaelven, Glama) show significant increases due to climate change, while human water use only results in small decreases by an order of magnitude less. For most central European basins, the water use impact is substantially larger and dominates the combined response. These basins are subject to substantial water withdrawals and water consumption (Fig. 3), especially resulting in widespread impacts during the driest period of the year. Since central Europe is located in between wetting signals in Scandinavia and drying signals in the Mediterranean, the climate change response is relatively weak. For the southern Ebro and Tejo basin, however, the combined response is largely driven by climate change.

The impact on high flows is, again, considerably smaller, only ranging between +/- 10% for most European basins. Exceptions are the two southernmost basins (Tejo, Guadiana), that are not just subject to major uncertainties in the climate change response, but also show high potential for large decreases in average annual peak discharge and high flows.

Based on the full ensemble of hydrological impact simulations forced by EURO-CORDEX regional climate model data, the **key findings** are:

1. Current and projected water use considerably impacts historic and projected low flows (both at the 5th percentile and regarding annual peak low flow) in southern and central Europe, leading to declines of up to 50% in comparison to pristine, natural conditions.
2. The climate change response leads to substantial declines in low flows in southwestern Europe and results in increasing low flows towards north-eastern Europe and in Alpine regions.
3. The combined response of decreasing low flows in southern and central Europe due to both climate change and water use leads to amplified declines in low flow conditions
4. Climate change and, to a lesser extent, also water demand impacts are subject to substantial model uncertainties originating from the full EURO-CORDEX ensemble
5. Relative differences in high flows are less pronounced and range within +/-10 of high flow conditions under pristine, natural conditions. However, relative changes of up to 10% can still lead to substantial changes in absolute discharge.

3.3.4 Impacts of current water use in a warmer world

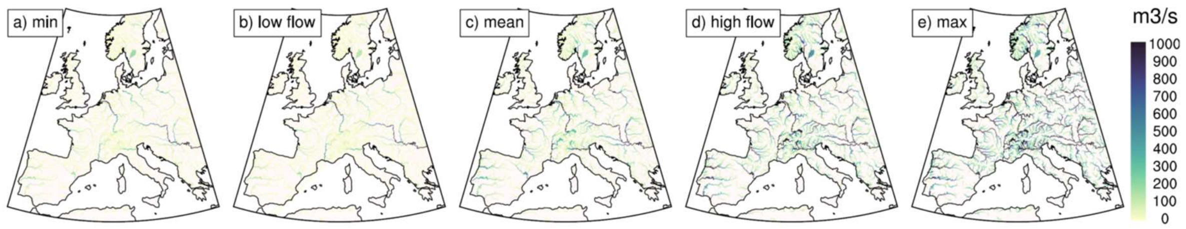

Figure 9: Daily discharge statistics based on KNMI-ref under CWatM-nat: (a) Average annual peak (lowest) low flow, (b) low flows representing the 5th percentile, (c) mean daily discharge, (d) high flows representing the 95th percentile, and (e) average annual peak discharge.

Based on the set of KNMI-PGW experiments provided as forcing to CWatM, peak discharge and low/high flow estimates under natural conditions in the reference period (1981-2010, nat-ref) are shown in Fig. 9 (within the smaller subdomain of the KNMI-PGW forcing data). Similar to the ensemble-average of the EURO-CORDEX-based simulations (Fig. 4), mean daily discharge tops well above 1000m^3/s in most of the major European river basins, while average annual daily peak low flows and low flows (at the 5th percentile) are considerably smaller (500 m^3/s and less), especially across the southern European basins. Differences between low and high flows in major central European basins (e.g., the Rhine river) are smaller, indicating relatively large discharge values also under low flow conditions.

Comparing peak low and high discharge under nat-ref to the other experiments, reveals insights on the impact of historical human water use and climate change on annual peak hydrological extremes across Europe (Fig. 10). However, in comparison to the impact simulations based on the EURO-CORDEX ensemble (considering future water demand based on SSP2, Fig. 6), it is now possible to evaluate the impact of historic water use under conditions of 2K global warming. While the general pattern of southern European drying and northern European wetting is evident, relative changes are indeed more pronounced, indicating a stronger influence of current water use conditions on annual

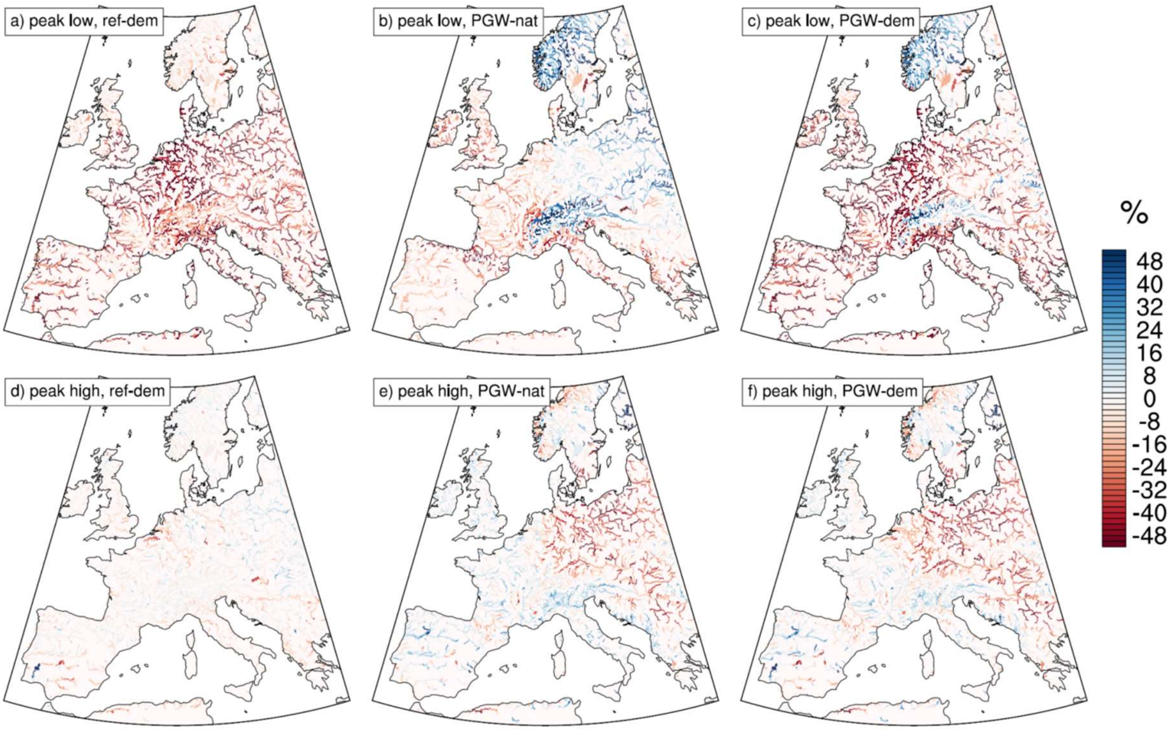

Figure 10: Relative difference (in percent) in annual peak low flows (upper row) and annual peak discharge (bottom row) between nat-ref and (a,d) dem-ref, (b,e) nat-fut, and (c,f) dem-fut. The left column (a,d) illustrates the impact from historical human water use on peak flows, whereas the middle column (b,e) illustrates the climate change impact. The combined impact is shown in the right column (c,f).

peak low/high discharge in a warmer climate. Regarding peak (high) discharge, the climate change response is more pronounced, leading to substantial decreases (up to 30%) in central-eastern European rivers and basins.

Taking a closer look at the distribution of annual peak low flows within the selected basins (see Fig. 2) illustrates the large shifts towards drier conditions in most central and southern European basins (Fig. 11). However, while changes in climate (corresponding to 2K global warming) both alter the shape and the position of the distribution, the addition of water demand mostly leads to stronger impacts in the median response, while somewhat preserving the shape. Largest difference in median annual peak low flow due to the addition of water demand are found for, e.g., the Elbe, Rhine, Moselle, and Tiber river, while a 2K global warming response heavily impacts the Upper Danube, the Tanaro, and the Rhone river.

Regarding changes in low/high flows, Fig. 12 illustrates the probability of experiencing the same low/high flow occurring under nat-ref in the other experiments. For example, if under nat-ref the absolute low flow discharge is 100m^3/s (i.e., at 5% of all days, discharge is at or below 100m^3/s), while under dem-ref discharge values of 100m^3/s or below occur at 10% of all days, the probability of experiencing nat-ref low flow values under dem-ref conditions is doubled. The probabilities shown in Fig. 11 indicate a widespread doubling of low flow probabilities across southern and central Europe under water use conditions (ref-dem). In parts of the Netherlands and northern Germany, low flows that occur at 5% of all days under nat-ref now occur at up to 25% of all days under ref-dem (indicating a 5-times probability increase). Under climate change conditions

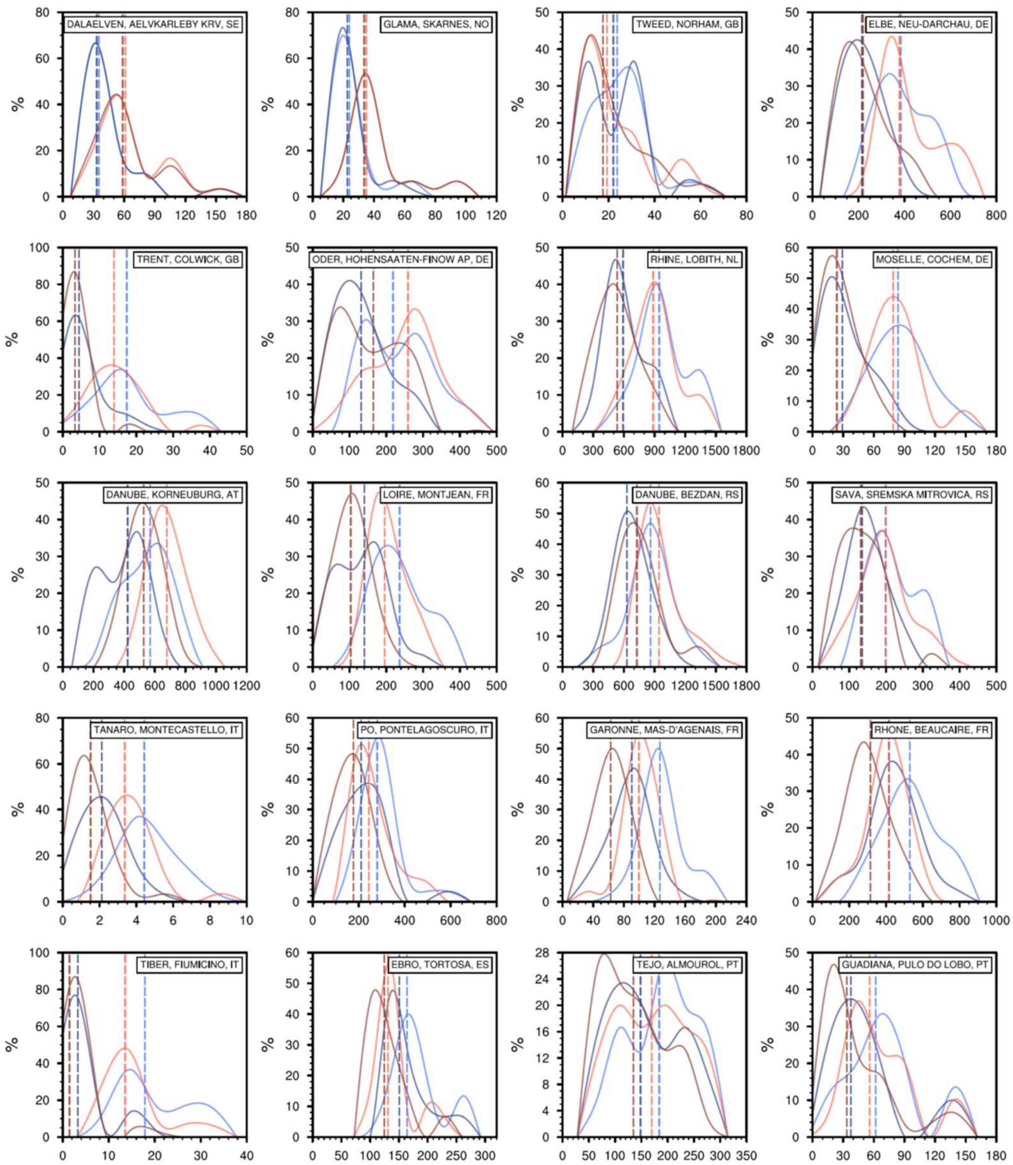

Figure 11: Differences in the probability distribution (in percent) of annual peak low flows in the selected basins based on the full period (1981-2010). Light colors denote natural conditions (nat), darker colors conditions considering water demand (dem). Blue colors denote reference conditions, whereas red colors denote conditions under 2K global warming. Please note that a spline was applied for a smooth illustration of the probability distributions. Dashed vertical lines show median annual peak low flows within the individual experiments.

corresponding to 2K global warming, low flow probabilities are widely doubled in parts of the Iberian Peninsula, while probabilities of experiencing nat-ref low flows are up to 5 times smaller in Alpine regions and Norway. The combined response shows a widespread increase of low flow probabilities across southern and central Europe. Regarding high flows, the probability of experiencing the same high flow occurring under nat-ref is largely unchanged in the other experiments.

Due to the pronounced response regarding low flows, Fig. 13 and Fig. 14 provide a more detailed look on low flow statistics in the selected basins (see Fig. 2). Fig. 13 illustrates the lower tail (up to the 10th percentile) of the daily discharge cumulative distribution. Impacts due to 2K global warming and/or due to the addition of water demand are different among several catchments. In the northern European catchments (Dalaelven, Glama), the lower tail is shifted towards larger discharge

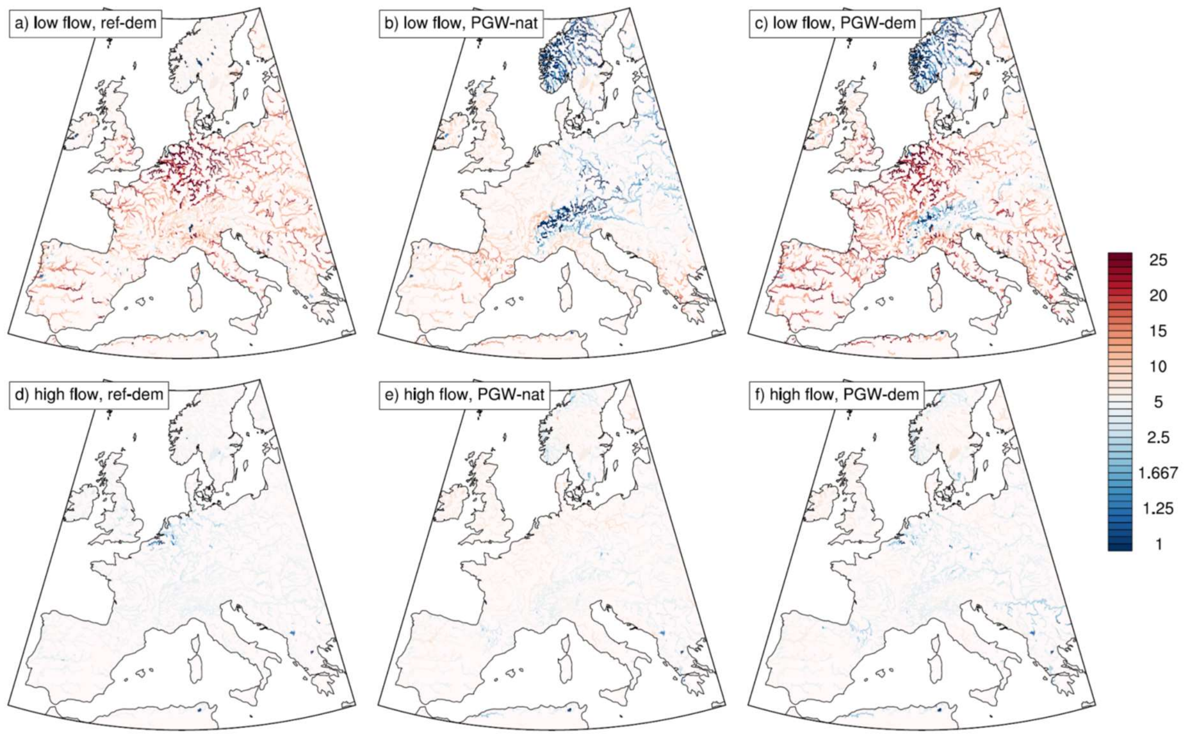

Figure 12: Probability for experiencing the same annual low flow (upper row) and high flow (bottom row) as in nat-ref in (a,d) dem-ref, (b,e) nat-fut, and (c,f) dem-fut. Orange/Red (blue) colors indicate the probability increase (decrease) of experiencing discharge values similar to low/high flows (5th / 95th percentile) as occurring in nat-ref. The left column (a,d) illustrates the impact from human water use on low/high flows, whereas the middle column (b,e) illustrates the climate change impact. The combined impact is shown in the right column (c,f).

values, while the addition of water demand only results in minor declines. In the majority of other basins, the water demand response is more pronounced and usually exceeds the climate change response, especially in the Oder and Moselle basin, where no changes due to 2K global warming occur. However, a few basins (e.g., the Upper Danube, Rhone, and Tejo river) show equal responses related to 2K global warming and under the consideration of water demand. The addition of water demand in the Tiber river, leads to modelling results simulating the river running dry (occurring at 0.5% of all days under dem-ref and 2% of all days under dem-fut).

A more detailed look on the low flow probabilities as shown in Fig. 12, reveal mixed responses at basin level (Fig. 14). The consideration of water demand increases low flow probabilities by up to 20% and more in the Elbe, Moselle and Tiber river. At least a doubling of low flow probabilities is found in most other basins. Combined with increasing low flow probabilities under conditions of 2K global warming, a widespread increase in the occurrence of low flows is found across most southern and central European basins.

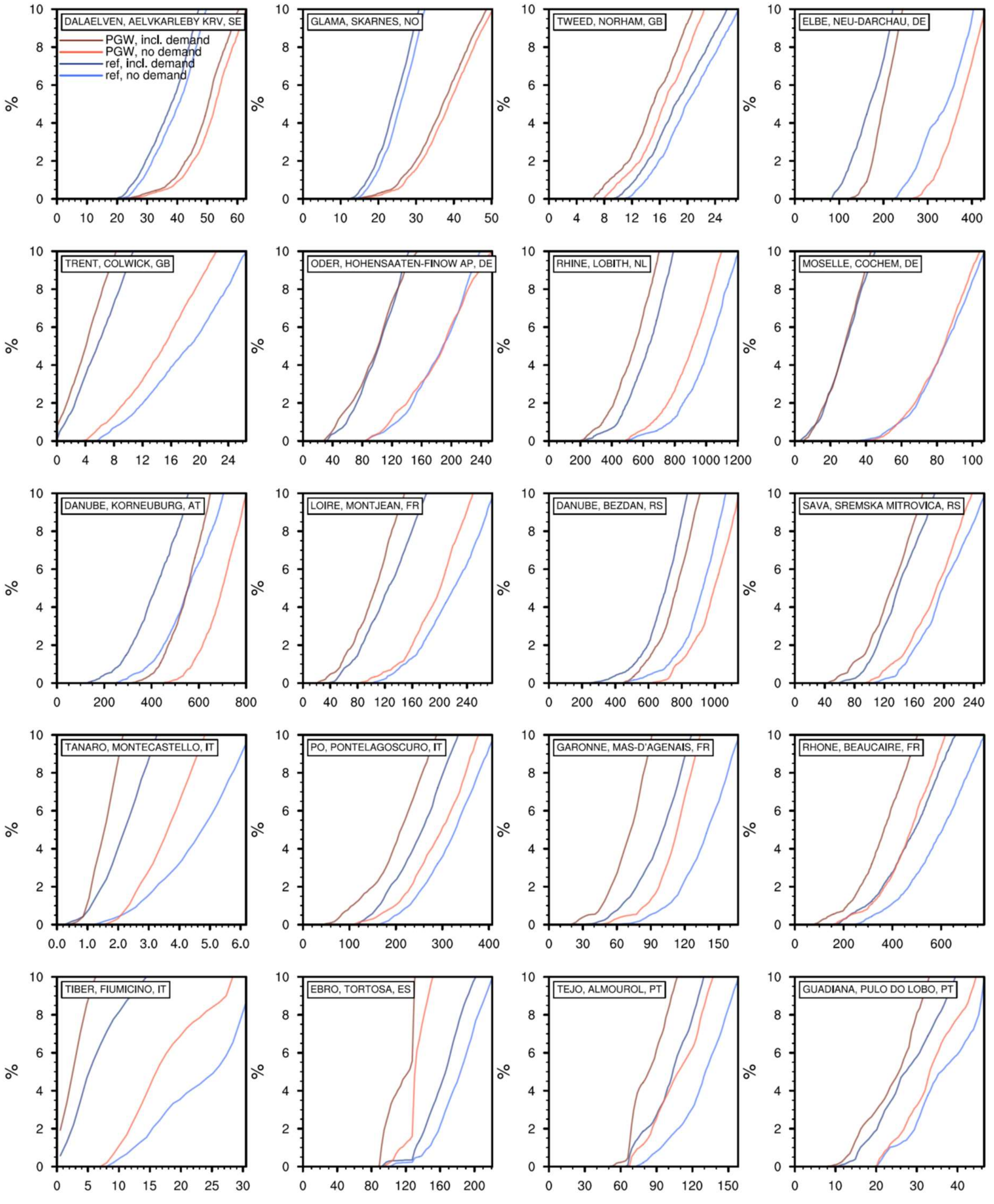

Figure 13: Differences in the lower tail (up to the 10th percentile) of the full probability distribution (in percent) of daily discharge in the selected basins based on the full period (1981-2010). Light colors denote natural conditions (nat), darker colors conditions considering water demand (dem). Blue colors denote reference forcing conditions, whereas red colors denote conditions under 2K global warming.

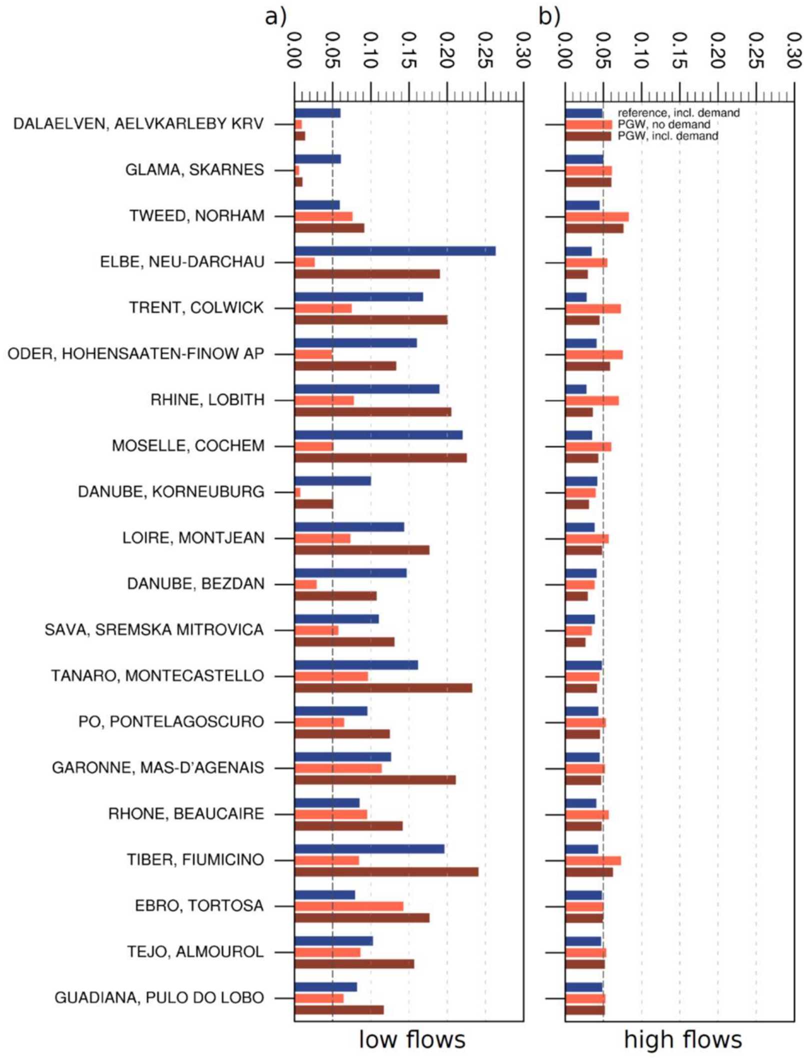

Figure 14: Probability for experiencing the same a) annual low flow, and b) high flow as in nat-ref in dem-ref (blue), nat-fut (light red), and dem-fut (dark red). Values larger (smaller) than 0.05 (dashed line) indicate the probability increase (decrease) of experiencing discharge values similar to low/high flows (5th / 95th percentile) as occurring in nat-ref.

Based on the set of hydrological impact simulations forced by KNMI-PGW regional climate model data, the **key findings** are:

1. Historic water use will exacerbate annual peak low flows and low flow probabilities across southern and central Europe under conditions of 2K global warming.
2. 2K global warming under historic water use leads to substantial declines in low flows in southwestern Europe and results in increasing low flows in Scandinavia and in Alpine regions.
3. Relative differences in annual peak discharge are less pronounced, but reach considerable values in parts of central and eastern Europe
4. Extreme low flows under the consideration of water demand increase the potential for rivers almost running dry in smaller, heavily managed southern European basins. (in particular, the Tiber and Tanaro river)
5. The pseudo-global warming experiments provide single estimates of projected conditions. Robust uncertainty assessments (in comparison to the rather large EURO-CORDEX ensemble) are missing to date.

4. Lessons Learnt and links Built

4.1. Summary and conclusions

Within EUCP, IIASA developed a large-scale hydrological and water resources model that can be used in climate change impact assessment at regional to global scales (Burek et al., 2020, Greve et al., 2020). By using high-resolution climate forcing data, impacts on hydrological extremes under water use and climate change conditions have been assessed.

Based on different modelling experiments, climate and water demand impacts on annual peak discharge and low/high flows have been singled out and assessed across Europe. In comparison to previous research excluding water demand estimates (e.g., Thober et al., 2018), the research presented in this report illustrates the significant impact of human water use particularly on low flows. It has been argued before (van Loon et al., 2016), that hydrological droughts are in parts driven by human influences on rivers and streams. The findings presented here largely support this statement and urge for a more comprehensive assessment of current and future risks and losses due to hydrological extremes by accounting for both climate and socio-economic change.

The presented results further highlight the Mediterranean region as a hotspot of climate change. It is likely that future climatic conditions will decrease flows in both the driest and wettest periods of the year. Low flows in dry periods will decrease substantially, thereby not just threatening domestic, agricultural and industrial water supplies, but also environmental flows and water-dependent ecosystems (and increasing the risk of river running dry). A major challenge of future water management is the increasing irrigation water demand under these conditions. However, also central Europe is at risk of facing water shortages in the driest periods of the year. It is shown that low river flows are already heavily impacted by current water use. Hence, water management must address the potential of more severe low flows by regulating water demand especially within dry, low flow periods.

4.2. Outlook and collaboration

The research presented in this report will be the starting point for further explorations of water use impacts on hydrological extremes. The next steps will include assessments of extreme value statistic and return periods based on the obtained time series. A closer look on outstanding extreme events (such as e.g. the record-breaking drought/heatwave in 2003) and their impacts within the KNMI-PGW setup is also intended, thereby strengthening the existing collaboration between IIASA and KNMI within the EUCP project. Further, initial results using weighting and sub-selection methods developed in WP2 (not shown here) show the potential for reducing uncertainties, subsequently leading to more robust conclusions. Close collaboration with several partners contributing to WP2 has already been established in fall 2019. It is planned to further extend the set of model simulations. Hydrological impact projections based on the EURO-CORDEX ensemble are now based on SSP2. It is planned to generate ensembles also based on SSP1 and SSP3. Regarding the KNMI-PGW experiments, KNMI will provide pseudo-global warming experiments based on (i) the HadGEM, and (ii) MPI-ESM climate models (besides EC-EARTH as presented within this report). The full ensemble of historical and climate change impact simulations based on the EURO-CORDEX forcing will be made publicly available via common data sharing platforms.

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