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Impact of a changing climate, land use, and water usage on Europe's water resources

A model simulation study

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Contents

Foreword

This report describes an assessment of the projected future impacts of climate change, land use change and changes in water consumption on Europe's water resources, as obtained using JRC's LISFLOOD water resources model. This assessment is done within the framework of the PESETA III climate project executed by JRC for DG CLIMA.

The LISFLOOD model is being developed by JRC since 1997 and is used in the flood early warning system EFAS, the drought System EDO, and the global flood alert System GloFAS. The model is frequently updated, improved, extended, calibrated and validated against observed data.

During the past years, we included some 'lessons learnt' from the water resources simulation work we did for 2012 "Blueprint to safeguard Europe's water resources" (De Roo et al., 2012). We realised back then that a few model improvements were needed and that the model domain needed to be extended to include Cyprus and the Mediterranean. We included also projected land use changes for non-EU28 countries in the Danube river basin. Furthermore, we carried out a detailed re-assessment of water demand and consumption (work of Bernhard & Reynaud). Also, the recent PhD work of Mr. Bernhard on EU water demand (Bernhard et al, 2018a,b) is included in this modelling exercise.

For this study, two 30-year climate windows were investigated and compared to the 1981-2010 control climate window.

A 30-year window around the year that global warming reaches 2°C at global scale has been analysed, to assess the consequences of climate change if Europe would meet the targets of the Paris climate agreement of December 2015. Depending on the level of emission reductions, the 2 degree global temperature increase limit may be reached already around 2040 (ensemble average of 11 climate models) when there would be limited mitigation (RCP8.5 scenario), or much later this century – or never - when there would be subtantial mitigation and thus reduced emissions.

For a more worst-case situation and its effects, a further window 2070-2099 under an RCP 8.5 emission scenario was investigated as well. This reflects a situation where global temperature increase is already 4.0-6.2 °C over preindustrial levels.

Acknowledgements

This study could only be achieved thanks to the many persons that throughout the years helped to develop, improve, validate and calibrate the LISFLOOD model and all its related input data. Many of these colleagues already departed from JRC after finishing their contracts (Peter Burek, Hylke Beck, Niko Wanders, Johan Van Der Knijff). But thanks to this community we are where we are now.

The EURO-CORDEX community http://euro-cordex.net/ is gratefully acknowledged for the supply of the climate projections. Within JRC, they have been further bias-adjusted by Allesandro Dosio (2016).

Also, the European Environment Agency (EEA), and especially Mr. Nihat Zal, is acknowledged for their collaboration and data sharing related to the water accounts and the water exploitation índex for historical periods. Mr Hans-Martin Füssel is thanked for his useful comments.

Beyond the author and co-authors of this report, this recent work is a collaborative effort within the JRC with several Units contributing. Specifically mentioned are Alessandro Dosio, Peter Salamon, Luc Feyen, Goncalo Gomes, Valerio Lorini, Lorenzo Alfieri, Carlo Lavalle, Chris Jacobs, Vera Thiemig & Zuzanna Zajac. Valuable feedback has been received also from Alberto Pistocchi, Faycal Bouraoui, Anna Malago and Giovanni Bidoglio.

Abstract

This report describes an assessment of the projected future impacts of climate change, land use change and changes in water consumption on water resources for the European continent, as obtained using JRC's LISFLOOD water resources model. For this study, two 30-year climate windows were investigated and compared to the 1981-2010 control climate window.

A 30-year window (on average 2026-2055) around the year that global warming reaches 2°C at global scale has been analysed, to assess the consequences of climate change if Europe would meet the targets of the Paris climate agreement of December 2015. Depending on the level of emission reductions, the 2 degree global temperature increase limit may be reached already around 2040 when there would be limited mitigation (RCP8.5 scenario) or much later this century – or never - when there would be subtantial mitigation and thus reduced emissions.

For a more worst-case situation and its effects, a further window 2070-2099 under an RCP 8.5 emission scenario was investigated as well. This reflects a situation where global temperature increase is already 3.5-4 degrees.

We conclude in this report that meeting the objectives of the Paris Climate Agreement of 2015 will lead to substantially less severe impacts for the water resources in Europe as compared to the impacts of climate change beyond 2 degrees global temperature increase. Issues with flooding and especially summer water scarcity are projected to increase.

A North-South pattern emerges across Europe for water availability under a 2°C warming scenario. Overall, Southern European countries are projected to face increased water shortages, particularly Spain, Greece, Cyprus, Italy and Turkey.

The contribution of land use changes and water demand changes combined are in the order of 10-20%, whereas climate is responsible for 80-90% of the projected changes.

The severity of impacts under the 2°C warming scenario suggests that mitigation alone is not enough to avoid adverse climate change impacts; adaptation strategies such as water savings and efficiency measures will be needed too.

SURFACE WATER AVAILABILITY

The results of the water resources impact simulation under a 2°C warming scenario, including climate change, land use change and water demand changes show a North-South pattern across Europe for water availability. Overall, Southern European countries are projected to face decreasing water availability, particularly Spain, Portugal, Greece, Cyprus, Malta, Italy and Turkey. Central and Northern European countries show an increasing annual water availability. The extremer RCP8.5 2070-2099 warming scenario displays the same spatial pattern as under the 2°C warming scenario, but more extreme in the amounts of increasing and decreasing water availability.

Seasonal analysis shows a marked differences between summer and winter streamflows, especially in France, Belgium and the UK. These three countries are projected to experience wetter winters and drier summers, with increased water availability in winter, and decreased water availability over the summer months. The extremer warming scenario shows again the same spatial pattern as under the 2°C warming scenario, but more extreme in the amounts of increasing and decreasing water availability.

GROUNDWATER

Under a 2 degree warming scenario, Spain (-3272 Mm3/year), Portugal (-1080 Mm3/year), and Greece (-810 Mm3/year) are estimated to have significant reductions in groundwater recharge. The groundwater recharge reduction estimated for Spain - 3272 Mm3/year – is 15% of the reported annual amount of abstracted water for irrigation.

CURRENT PRESSURES ON WATER RESOURCES ARE EXACERBATED IN SOUTHERN EUROPE

The Water Exploitation Index (WEI+) is a metric that takes account net water consumption versus available renewable water resources. Values below 0.2 indicate areas without major water scarcity. Areas with values between 0.2 and 0.4 experience water scarcity in at least a part of the year. Areas with a WEI+ larger than 0.4 or often water scarce during a year. This indicator does take into account inflowing river water from cross-border river basins. According to this index, water scarcity is a regular issue already in some parts of Europe.

The water resources situation becomes more unsustainable under a 2°C warming scenario for countries in the Mediterranean, and especially Spain. Under the RCP8.5 end of the 21st century scenario, water scarcity would be even more widespread expanding even to central Europe. Overall, Southern European countries are projected to face increased water shortages.

WATER SCARCITY AFFECTED AREAS AND PEOPLE

Under an extreme warming scenario, the number of persons affected by water scarcity in EU28 countries could increase at the end of the 21st century from the current 85 million to 104 million (Mediterranean - robust) or potentially 295 million (EU28 - less robust). Under the 2°C warming period it is projected that the number of affected people increases slightly from 85 to 94 million persons, mainly in the Mediterranean countries.

If water demand stays at current usage levels and without significant water saving efforts, the warming climate and reduced precipitation in the Mediterranean causes extreme increases in water scarcity. The people already affected under current climate will encounter much intenser water scarcity than at present.

RUNOFF IN CITIES

Local runoff production is increasing under the 2°C warming scenario as a consequence of climate change and urban expansion. This could cause local water excess problems and sewer overflows. Most likely many urban areas are projected to be more vulnerable for pluvial flooding in a future climate. Some Mediterranean cities, such as Lisbon and Seville are projected to have decreased annual runoff.

SOIL MOISTURE STRESS

Under a 2 degree warming scenario, there is a tendency of increased soil moisture stress in large parts of Europe, including France and UK. Areas which are currently already often stressed in the Mediterranean will become even more stressed under the 2°C warming scenario.

LOW FLOW

The projections for low flow conditions under a 2 degree climate together with projected land use and water demand change or Europe show again the North-South pattern, with typically increased low flow and drought issues in the Mediterranean countries.

HIGH FLOWS

For autumn and winter months, the projections indicate increased high flows almost everywhere in Europe, with river discharges at that frequency increasing by 10-30%. The springtime months show a decrease in high flows around the Baltic Sea, very likely related to decreasing snow amounts under a warmer climate, and thus less problems with snowmelt floodings. The summer months especially show increased high flows in Central and Eastern Europe.

Under the extreme warming scenario, the projected changes indicate the same spatial pattern of high flow changes as under the 2 degree warming, but the magnitudes of the high flows are more extreme.

HYDROPOWER

We project for the 2-degree climate change a 4% decrease of hydropower annual inflow for the SW European region, consisting of Spain, Portugal, Southern France and Northern Italy. A 2% reduction is projected for the SE European region, consisting of the Balkans, Greece and Southern Italy. However, both decreases and increases are projected within these regions. For NE Europe, we project increases for hydropower locations with around 13%, potentially leading to local dam safety issues.

For the end of the century RCP8.5 climate, we do project a far more extreme picture, with 12% decreases in hydropower inflow in the SW European region (Spain, Portugal), and 10% decreases in the SE region (Greece, Balkans). For NE Europe, we project increases for hydropower locations with around 28%, potentially leading to dam safety issues.

COOLING

We project significant decreases of low flows of around 25% in the SW European region (Spain, Portugal, Southern France, parts of Italy) and also in the SE European region (Greecse, Southern Italy, Balkan countries). This might lead to cooling water availability issues for termal power stations, in addition to the higher temperature of the cooling water under the warming scenarios. For Scandinavian countries and Eastern European countries, low flows are improving.

THE NEED FOR ADAPTATION

The severity of some of the projected changes in water availability presented here, which are under a global warming scenario in line with the Paris Agreement, suggests that various adaptation mechanisms will be needed to lessen the effects of climate change on European water resources, even under a 2°C warming scenario.

Projected increases in water dependency for some regions calls for sustained water diplomacy between countries as well as international multi-member-state management of river basin water resources. In Europe, this is already foreseen under the Water Framework Directive.

A number of planned adaptation strategies could be targeted at irrigation practices to lower pressures on water resources. Water pricing for irrigation water, as well as for industrial water, and public water, could create an incentive for users to consider water savings. Irrigation efficiency could be increased by changing irrigation methods (e.g from sprinkling to drip irrigation), but this is likely to only be feasible when irrigation water has a price. Furthermore, sub-optimal irrigation strategies may lead to only limited reductions in crop yields, but towards substantial water savings.

Other options might focus on delivering more efficient cooling technologies that lead to a reduction in water use for producing energy. In addition, shifts from conventional energy production (coal) to renewable energy production could reduce cooling water demand and net consumption.

Some of these measures are to some extent being implemented by European Memberstates within the Water Framework Directive. However, preliminary analysis suggests that planned MS measures on water efficiency improve the state of water resources under current climate, but may not be sufficient under a climate warming scenario.

1 Introduction

Freshwater is a precondition for human, animal and plant life as well as an indispensable resource for the economy (http://ec.europa.eu/environment/water/index_en.htm). The protection of European water resources is therefore subject to several EU legislations, such as the Water Framework Directive. Managing and coping with the extremes of water – floods and droughts – are covered under the Floods Directive (FD) and EU Action on Water Scarcity and Drought.

However, freshwater resources are under threat. In addition to the already existing pressures on Europe's freshwater, additional climate change effects may further deteriorate its availability and quality. One of the key expected impacts of global warming will be on water resources (Arnell and Gosling, 2013). And earlier studies (Dankers and Feyen, 2008) already projected that the magnitudes and frequencies of extreme events in Europe would likely increase as a result of climate change.

In view of ongoing global warming, climate change adaptation and disaster risk reduction have been recognized as a priority worldwide. This is exemplified by global frameworks such as the Paris Agreement and the Sendai Framework for Disaster Risk Reduction, and European actions like the EU Climate Change Adaptation Strategy. In the Paris Climate Agreement reached in December 2015, 195 countries joined forces to produce the first-ever global and legally binding climate agreement which aims to strengthen the global response to the threat of climate change (UNFCCC, 2015). The Paris Climate Agreement elevates adaptation to the same level and importance as mitigation and establishes the framework of limiting global warming well below 2°C and pursuing 1.5°C, while simultaneously enhancing adaptive capacity, strengthening resilience and reducing vulnerabilities.

Climate change and land use changes driven by political, demographical and economic factors will have consequences for the balance between water availability and water demand of various sectors. Quantifying these water allocation strategies but also the (socioeconomic) impact estimates of natural hazards (drought, floods) under different degrees of global warming is of high interest to inform and support climate policy makers for mitigation and adaptation strategies.

Land use change (LU), changes in water demand (WD) and climate change (CC) are important drivers in the hydrological cycle and large numbers of studies have evaluated the potential impacts of global warming on the different components of the hydrological cycle.

Recent improved detail in water use scenarios (Bernhard et al, 2018a, 2018b), which foreshadow possible future water consumption in Europe, further open new opportunities for an integrated assessment of water resources (Schaldach et al., 2012). Even if water use modules have been already embedded into a number of large-scale hydrological models to investigate water availability (Aus van der Beek et al., 2010, Flörke et al., 2012, 2013), there is still a need to better assess future water consumption related to water scarcity issues (Wada et al., 2013). Also, projected temperature and precipitation changes show a large sub-annual variability, and therefore a seasonal assessment of both water availability and demand should be undertaken (Kundzewicz et al., 2007).

2 The LISFLOOD hydrological model

The water resources calculations are done with the LISFLOOD 2.0 model. LISFLOOD 2.0 is a GIS-based spatially-distributed hydrological rainfall-runoff-routing model, developed at the EC-Joint Research Centre (JRC) since 1997 (De Roo et al., 2000; Van der Knijff et al., 2010; Burek et al., 2013). LISFLOOD V1 is primarily used for simulating river floods and flood forecasting. The updated LISFLOOD 2.0 model has been – in addition to flood forecasting - used for studies dealing with global, European and African water resources.

2.1 General description

Driven by meteorological forcing data, LISFLOOD 2.0 calculates a complete water balance at a daily time step and every grid-cell defined in the model domain (figures 1 and 2).

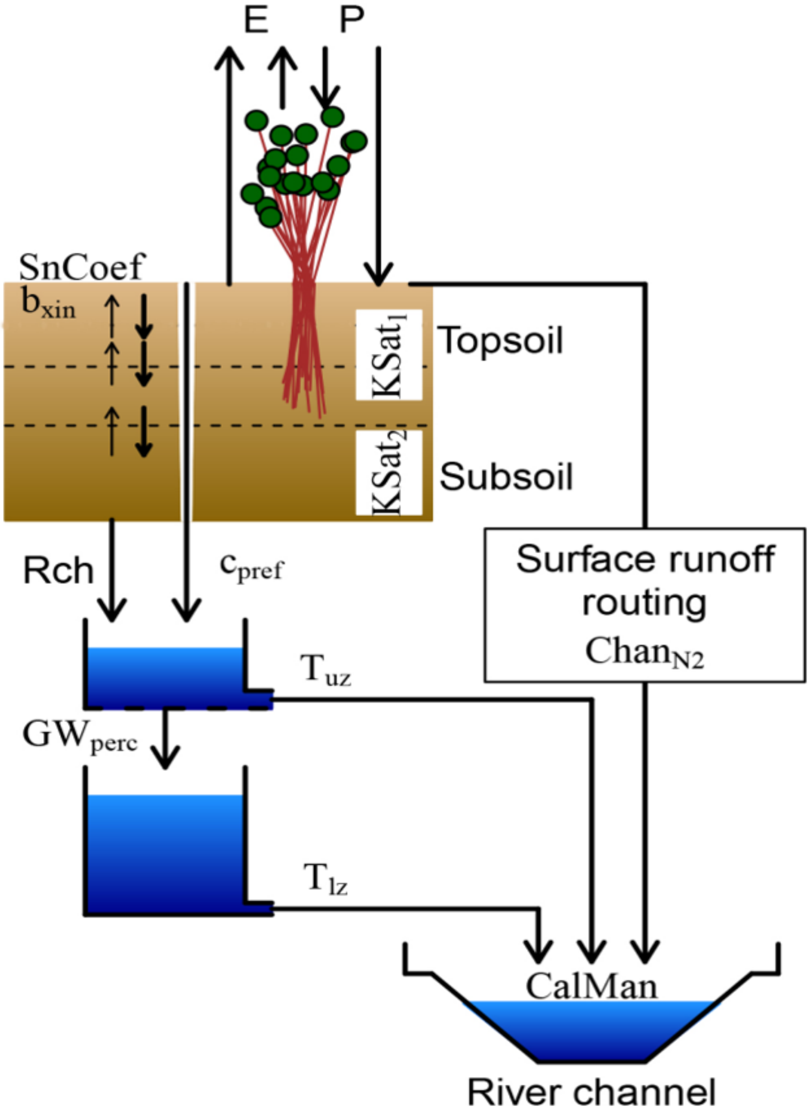

Figure 1 Structure of the LISFLOOD model, showing the main processes simulated in each model grid cell: three soil layers, and two groundwater layers, feeding water to the river channel network.

Processes simulated for each grid cell include snowmelt, soil freezing, surface runoff, infiltration into the soil, preferential flow, redistribution of soil moisture within the three-layer soil profile, drainage of water to the groundwater system, groundwater storage, and groundwater base flow. Runoff produced for every grid cell is routed through the river network, using a double kinematic wave approach, one for the main channel, and one for the floodplain.

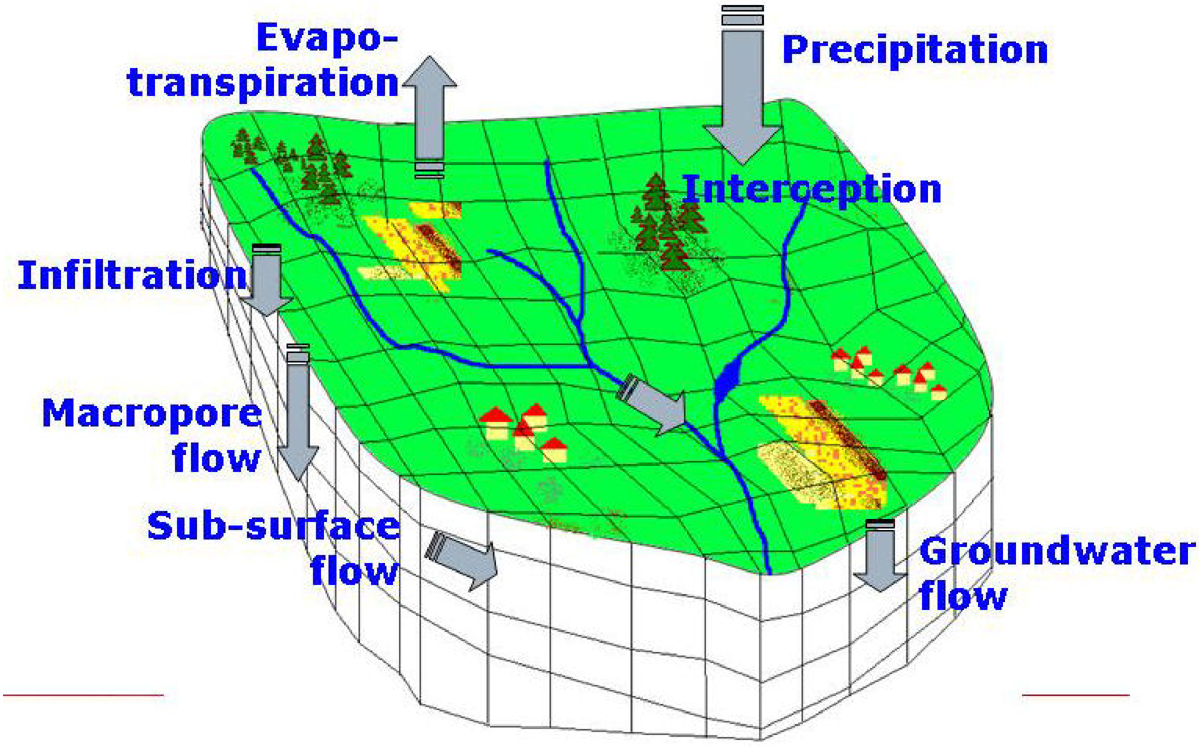

Figure 2 Spatial schematisation of the LISFLOOD model for a single river basin. LISFLOOD can be used for single river basins, entire continents, and at global scale.

Lakes, reservoirs and retention areas or polders are simulated by giving their location, size, inflow and outflow boundary conditions, and an estimation steering parameters. Since in many cases no data are available of the actual reservoir operations, an estimation of their steering rules has been with the assumption that on a multi-annual basis the reservoir volume stays the same.

Static maps used by the model are related to topography (i.e., digital elevation model, local drain direction, slope gradient, elevation range), land use (i.e., land use classes, forest fraction, fraction of urban area), soil (i.e., soil texture classes, soil depth), and channel geometry (i.e., channel gradient, Manning's roughness, bank-full channel depth, channel length, bottom width and side slope).

Soil texture and depth data were derived from the ISRIC 1km SoilGrids database (Hengl et al., 2014).

Elevation data was derived from the Hydrosheds database – using SRTM elevation data - (Lehner et al., 2008, http://www.worldwildlife.org/pages/hydrosheds). The river network was taken from the work by Wu et al. (2012).

Land use is derived from the 100m resolution Corine dataset for Europe.

2.2 Sub-Grid processing

While LISFLOOD 2.0 model is a regular grid-based model with a constant spatial grid resolution - in this study 5x5km grids - more detailed sub-grid land use classes are used to simulate the main hydrological processes. The model distinguishes for each grid the fraction open water, urban sealed area (figure 3), forest area, paddy rice irrigated area, crop irrigation area (figure 4) and other land uses derived from the 100m resolution CORINE and LUISA land use model. The sum of these 6 fractions is 100% of the grid.

Box 1. Sub-grid processes

While LISFLOOD 2.0 model is a grid-based model with a constant spatial grid resolution (for the European setup 5x5km grids), more detailed sub-grid information is used to simulate the main hydrological processes

The LISFLOOD 2.0 model used the following land use classes to calculate a number of hydrological processes:

- open water
- urban sealed area
- forest area
- paddy rice irrigated area
- crop irrigation area
- other land use

These 6 fractions should add up to 1=100% of the grid. Specific hydrological process (evapotranspiration, infiltration etc.) are then calculated in a different way for these land use classes. At the end of a model calculation timestep, the outgoing water fluxes are then accumulated and routed to the river network or groundwater etc.

Specific hydrological processes (evapotranspiration, infiltration etc.) are then calculated in a different way for these land use classes. Moreover, sub-gridded elevation information is used to establish detailed altitude zones which are important for snow accumulation and melting processes, and to correct for surface temperature.

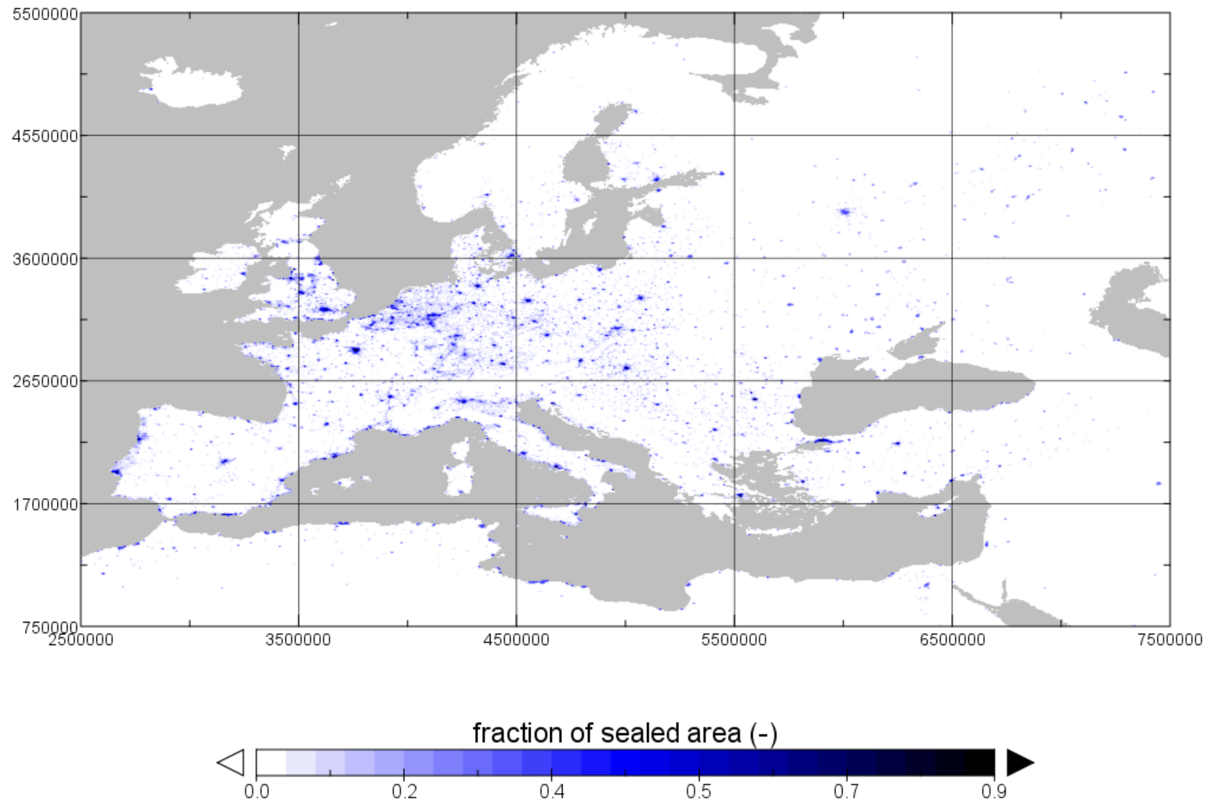

Figure 3 Fraction of sealed and urban areas (within a 5x5km model pixel), valid for 2010 (Source: Corine Land Cover).

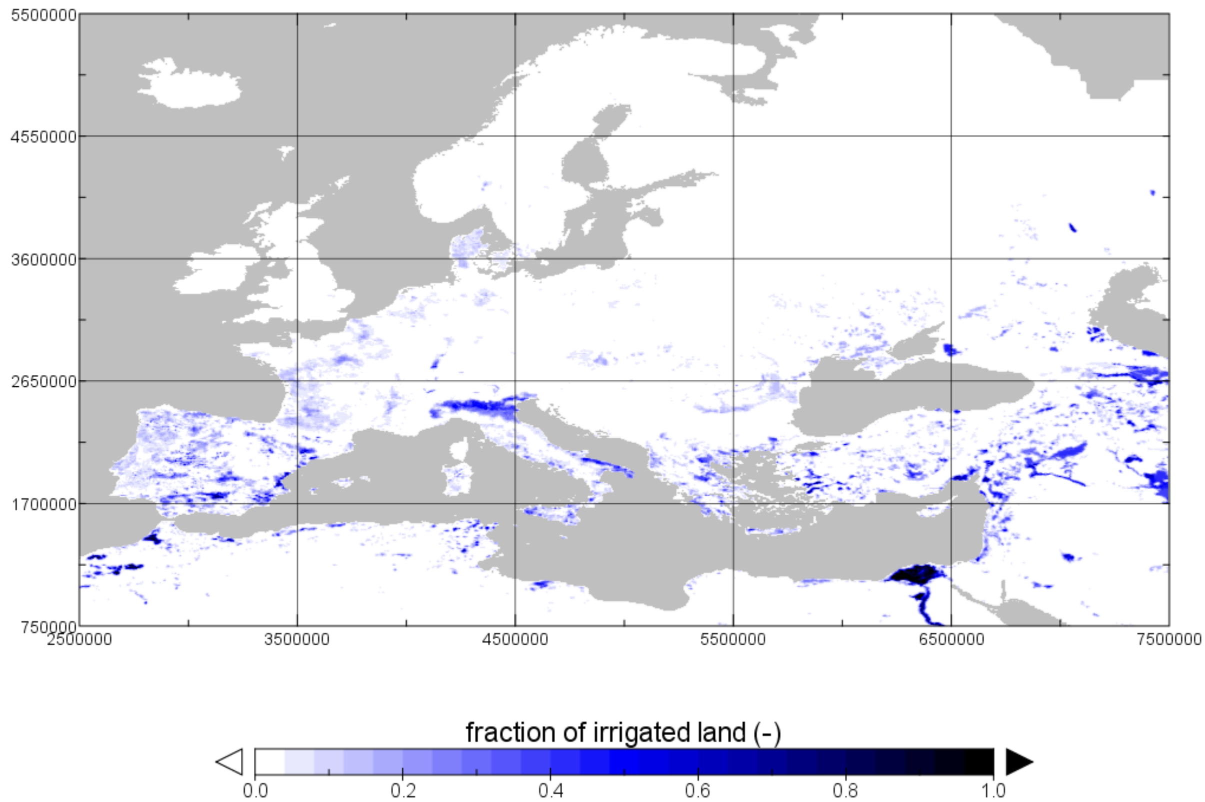

Figure 4 Fraction of irrigated areas (within a 5x5 km model pixel), valid for 2010 (Source JRC: Wriedt et al, 2009).

2.3 Simulating water demand and water consumption

Water demands (public water, livestock water, industrial water, cooling water for the energy sector, and irrigation) are abstracted from surface and/or groundwater resources (depending on the region) when available, taking into account a minimum discharge threshold in rivers, below which abstraction is not permitted.

Box 2. Irrigation water demand

The LISFLOOD 2.0 model includes an embedded irrigation water demand estimate. Using a Penman-Monteith approach, the model estimates the required amount of transpiration by vegetation or a crop. If this amount of water is not available from soil moisture above wilting point level, the missing amount is designated as the irrigation water demand.

Since irrigation efficiency is not equal to 100%, a larger amount than the strict required amount is abstracted.

Depending on the irrigation technique used (sprinkling irrigation, drip irrigation, others), and efficiency is set between 0 and 1 (fully efficient). If the irrigation efficiency is e.g. 80%, 125% of the irrigation requirement is needed in order to have 100% available for the irrigated crop.

In a similar manner, irrigation conveyance efficiency is taken into account. During transport of the irrigation water from its source to the location of application to the crop, water may be lost in irrigation channels due to evaporation or leakage. Again, values range from 0 to 1, where 1 means no losses occur. A conveyance efficiency of 0.8 would thus mean that another 25% more water needs to be abstracted to arrive finally at the application location.

A calendar is also used, by which the user may indicate between which dates irrigation is applied, and other time periods where irrigation is not applied.

When the abstraction requirement is defined, the model checks if abstraction is done from groundwater, or from surface water sources.

For paddy-rice irrigation, a different procedure is followed.

Using again a calendar file of field preparation, planting and harvesting of the rice crop, a paddy-rice field is first fully saturated. Following that a constant layer of typical 5-10cm water (user input) is applied, following which the rice is planted. The water layer is then held constant for a period until 20 days before harvesting. The amount evaporated daily is defined as paddy-rice irrigation water demand, and added by irrigation water.

Groundwater abstraction takes place if the region is reported to abstract a fraction of their water demand from water (source: FAO), and if an active aquifer exist (source: BGM)

3 Calibration and validation of the model

Within the LISFLOOD reference run, LISFLOOD uses gridded observed meteorological data from 1990-2016, the JRC EFAS-MARS meteogrids. LISFLOOD has been calibrated and validated using observed river discharge data obtained from the Global Runoff Data Centre (GRDC) or through direct access to discharge data from National Hydrological Services.

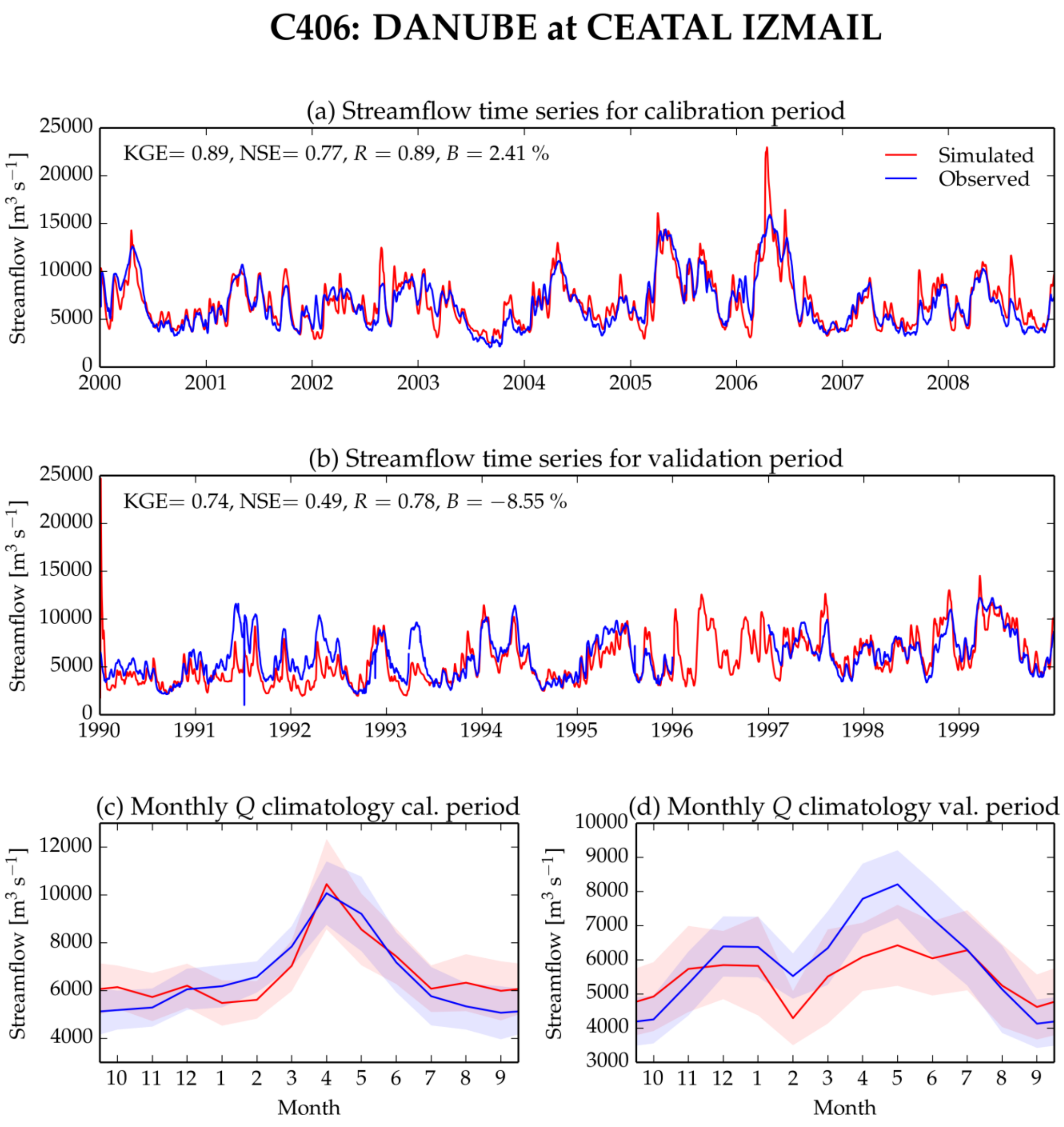

Figure 5 LISFLOOD calibration for Ceatal Izmail downstream in the Danube River Basin.

LISFLOOD was calibrated to improve the response behavior of the model. For the calibration we used as objective function the Kling-Gupta Efficiency (KGE; Kling et al., 2012) computed between simulated and observe daily Q. To evaluate the temporal transferability of the calibrated parameter sets, for each station the record of simultaneous forcing and observed Q data was split into a calibration and a validation period. In total 717 stations in Europe with at least 5 years with observed discharge data were selected for calibration. The number of generations was limited to 13, as this was found to be sufficient to achieve convergence in most cases. This resulted in 832 model runs and objective-function evaluations per catchment.

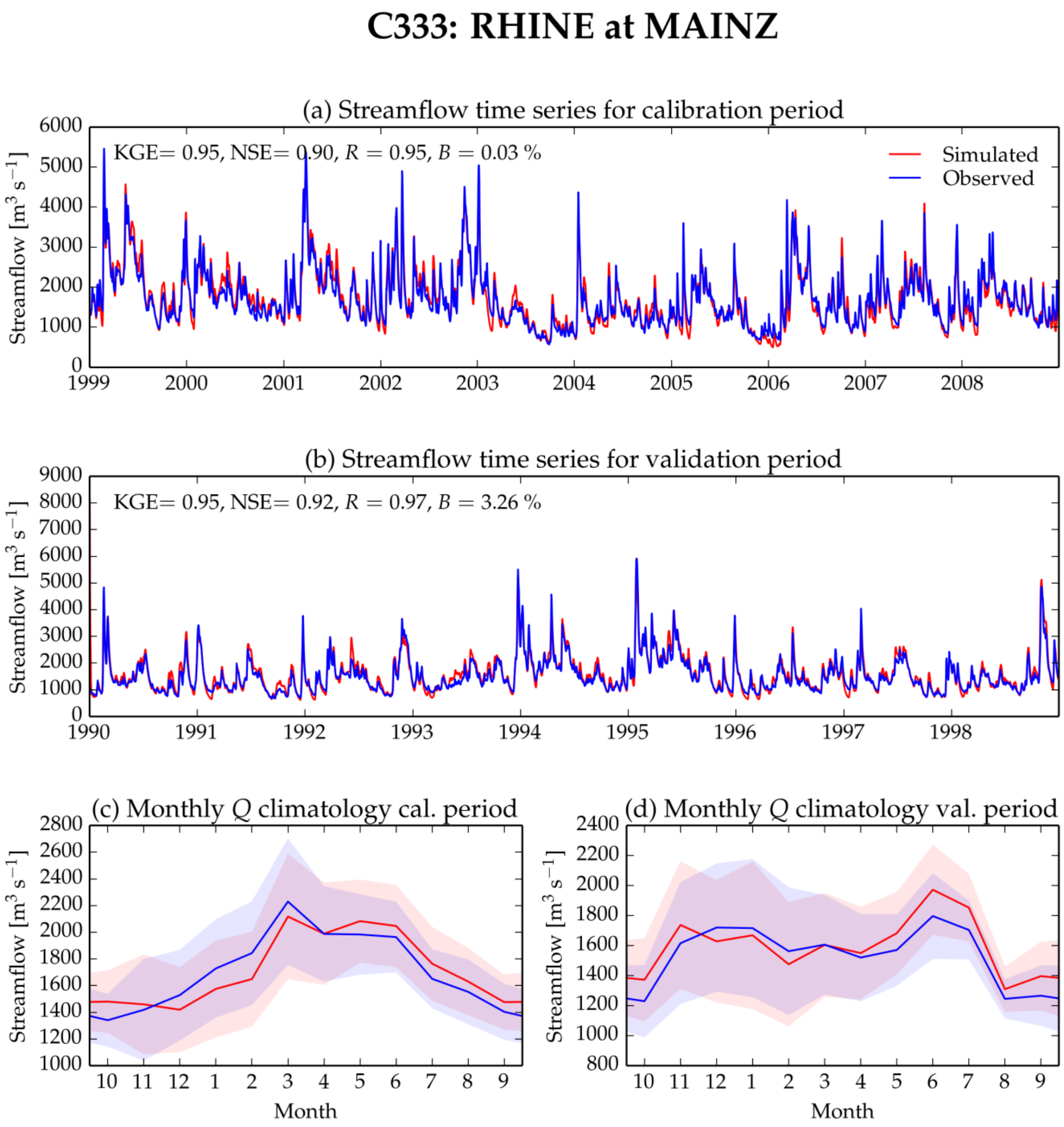

Figure 6 LISFLOOD calibration for Mainz in the Rhine river.

Figures 5 and 6 show the calibration and validation results of 2 stations in the Danube and Rhine river respectively. The KGE scores obtained from the calibration period for both stations suggest a very good model performance. The similar score of the KGE in the validation period for Mainz demonstrate the robustness of the obtained parameters, whereas a small decrease from calibration to validation scores are found for Ceatal Izmail due to overestimation of the simulated discharge.

Figure 7 shows a comparison of observed annual streamflow and simulated annual streamflow. The upper-left picture shows the comparison of the 'hindcast' 1990-2016 reference run of LISFLOOD using observed meteorological data, where observed and simulated annual flows are well corresponding. The other 11 pictures show the results of LISFLOOD forced with the 11 climate model control runs (1981-2010). Six climate models underestimate streamflow up to 20%, three models are reasonably close to the observed flow, and two models overestimate streamflow by 10-20%.

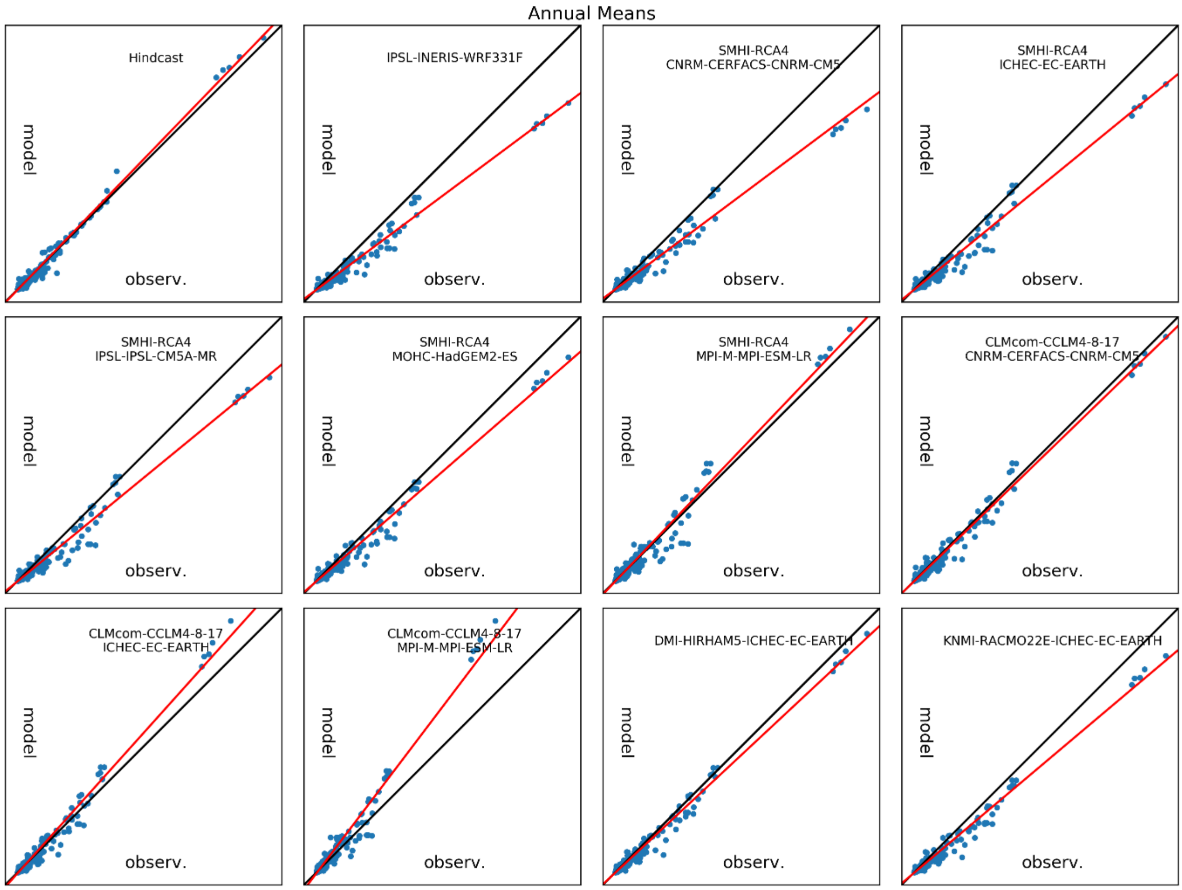

Figure 7 Comparison of observed and simulated annual streamflow using the LISFLOOD model, using the observed 1990-2016 meteorological data (upper left picture 'hindcast'), and for the 11 1981-2010 climate control scenarios described below.

4 Projected changes of temperature and precipitation.

In this study, 11 of the most recent available European EURO-CORDEX climate scenarios have been used.

4.1 CORDEX climate input data

The Coordinated Downscaling Experiment over Europe (EURO-CORDEX; Jacob et al., 2014) is an international climate downscaling initiative that aims to provide high-resolution climate projections up to 2100. Scenario simulations within EURO-CORDEX use the new Representative Concentration Pathways (RCPs) as defined in the Fifth Assessment Report of the IPCC (Moss et al., 2010). RCP scenarios are based on greenhouse gas emissions and assume pathways to different target radiative forcing at the end of 21st century. Within EURO-CORDEX, a number of Regional Climate Models (RCM's) to downscale a number of CMIP5 Global Circulation Models (GCMs).

In this work, historical climate scenarios (1981-2010) and future projections (2011-2100) from 11 EURO-CORDEX climate projections (see Table 1) under the RCP8.5 emissions pathways (Riahi et al., 2011) were used to drive the LISFLOOD hydrological model at a daily scale. The 11 EURO-CORDEX models were run at 0.11 degree horizontal resolution (~12km). Meteorological variables extracted are average (tas), minimum (tasmin) and maximum (tasmax) surface air temperature, total precipitation (pr), surface air pressure (psl), 2 m specific humidity (huss), 10 m wind speed (sfcWind), surface downwelling shortwave radiation (rsds), surface upwelling shortwave radiation (rsus) and surface upwelling longwave radiation (rlus).

Both the precipitation and temperature fields are bias-adjusted by JRC (Dosio et al., 2012), using the E-OBSv10 1981-2010 climatic observation-based dataset (Haylock et al., 2008) as a reference. A transfer function (Piani et al., 2010; Dosio and Paruolo, 2011) is used to tailor the data for the application in climate impact research.

All the meteorological variables are re-gridded at 5 km x 5 km. For each time step, the potential evapotranspiration maps are computed using the Penman–Monteith equation.

Table 1 Climate projections within CORDEX and the corresponding year of exceeding 2°C warming with the 30-year evaluation period.

	Institute	GCM	RCM	2°C	2 degree period evaluated
1	CLMcom	CNRM-CM5	CCLM4-8-17	2044	2030-2059
2	CLMcom	EC-EARTH	CCLM4-8-17	2041	2027-2056
3	IPSL	IPSL-CM5A-MR	INERIS-WRF331F	2035	2021-2050
4	SMHI	HadGEM2-ES	RCA4	2030	2016-2045
5	SMHI	MPI-ESM-LR	RCA4	2044	2030-2059
6	SMHI	IPSL-CM5A-MR	RCA4	2044	2030-2059
7	SMHI	EC-EARTH	RCA4	2041	2027-2056
8	SMHI	CNRM-CM5	RCA4	2035	2021-2050
9	DMI	EC-EARTH	HIRHAM5	2043	2029-2058
10	KNMI	EC-EARTH	RACMO22E	2042	2028-2057
11	CLMcom	MPI-ESM-LR	CCLM4-8-17	2044	2030-2059
			AVERAGE	***2040***	***2026-2055***

Ensemble water resources simulations are produced using the 11 EURO-CORDEX climate projections for the 30-year periods, centered on the year of exceeding the global-mean temperature of 2°C according the used Global Climate Model (GCM; Table 1). For the global models considered here, the 2 degree is reached on average around 2040 in the RCP8.5 scenario, which is when very little emission mitigation will take place.

To represent the baseline scenario, simulations using the 11 EURO-CORDEX data from the period 1981-2010 are performed and analysed. We executed runs with a changed climate only, and runs with a changed climate, land use and water demand. This approach allowed us to estimate the isolated and integrated effects of land use, water demand and climate change on future water resources, with the changes characterized as changes relative to the baseline.

Finally, also an analysis of all 11 EURO-CORDEX scenarios was made for the time window 2070-2099, and compared to the baseline 1981-2010 scenario. During this time window under the RCP 8.5 scenario, global temperature increase is already 3.5-4.0 degrees. This represents a situation when little emission reductions would be implemented and the Paris targets would not have been met.

4.2 Projected changes in temperature and precipitation in Europe.

Projected changes of temperature in Europe for an RCP8.5 end of the century climate are shown in Figure 8. Scandinavia is projected to experience much higher winter temperatures than the average global temperature increase. The Mediterranean and the Alps are projected to experience much higher summer temperatures than the global temperature increase.

Figure 9 shows the projection of temperature change in Europe when a global average temperature increase of 2 degrees is reached, the upper limit of the Paris climate agreement. Figure 9 shows that a 2 degree change on a global scale results in a ~3 degree change in Scandinavia and a ~1 degree change in the UK. Thus, large spatial differences can be observed.

Precipitation is by far the most important driver for water resources. Figure 10 shows the projected changes of precipiation in Europe for an RCP8.5 end of the century climate. In general, decreases are projected in the Mediterranean area both in winter and summer. For central Europe, increases in precipitation are projected for the winter months, but decreases for the summer months. For Scandinavia and the Baltic States increases in both summer and and winter are projected.

Figure 11 shows the projection of precipitation change in Europe when a global average temperature increase of 2 degrees is reached. Increases are projected predominantly in Scandinavia and Eastern Europe, while decreases are projected in the Mediterranean and Northern Africa. Monthly and seasonal patterns of change sometimes differ from this general annual average. That is why it is preferred to execute the water resources simulations at a daily time resolution, and results averaged at daily, monthly, seasonal or annual scale, depending on the observed trends.

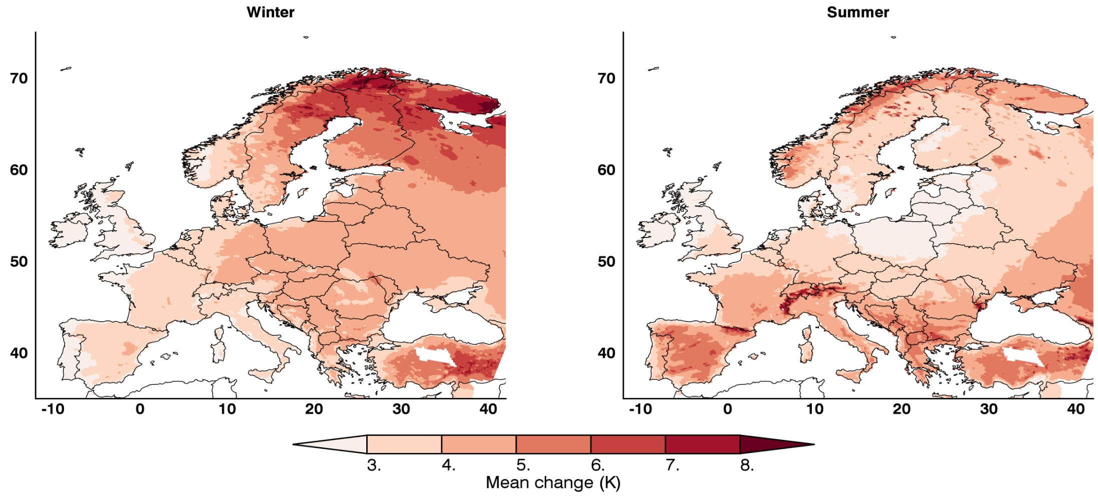

Figure 8 . Projected change of seasonal mean daily temperature for winter and summer, at the end of the century (2071-2100) compared to present day climate (1981-2010), under RCP8.5 (Source: Dosio, 2018)

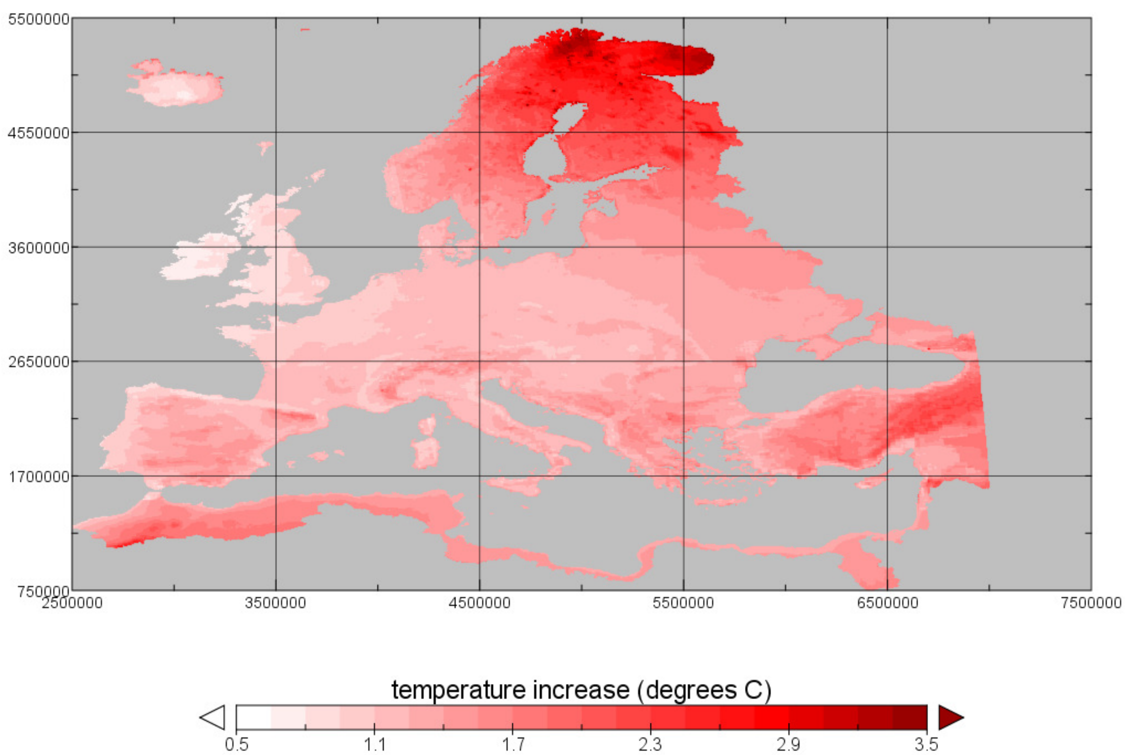

Figure 9 Projected temperature increase in Europe at the time when a global average temperature of 2 degrees is reached (average of 11 Euro-Cordex models).

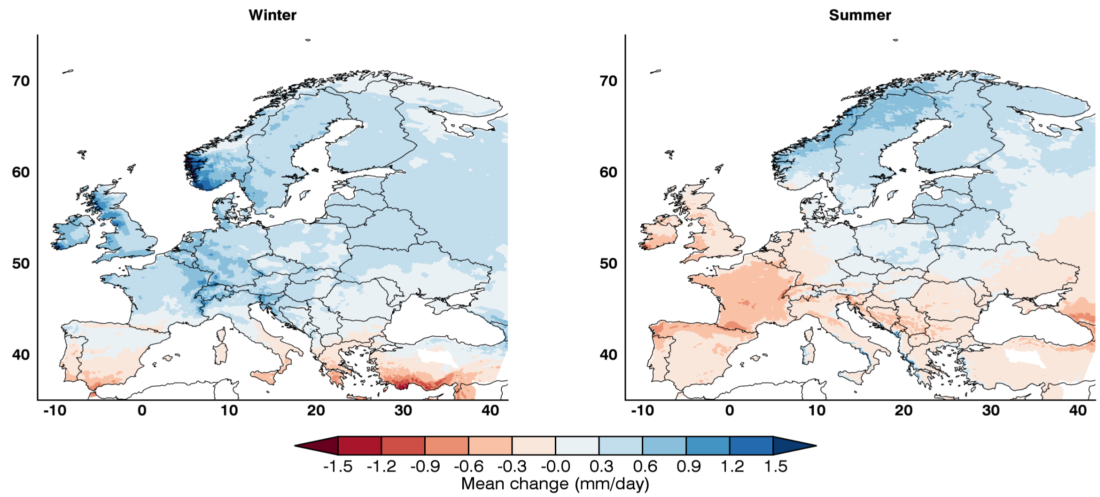

Figure 10 Projected change of daily precipitation in winter and summer, at the end of the century (2071-2100) compared to present day climate (1981-2010), under RCP8.5 (Source: Dosio, 2018).

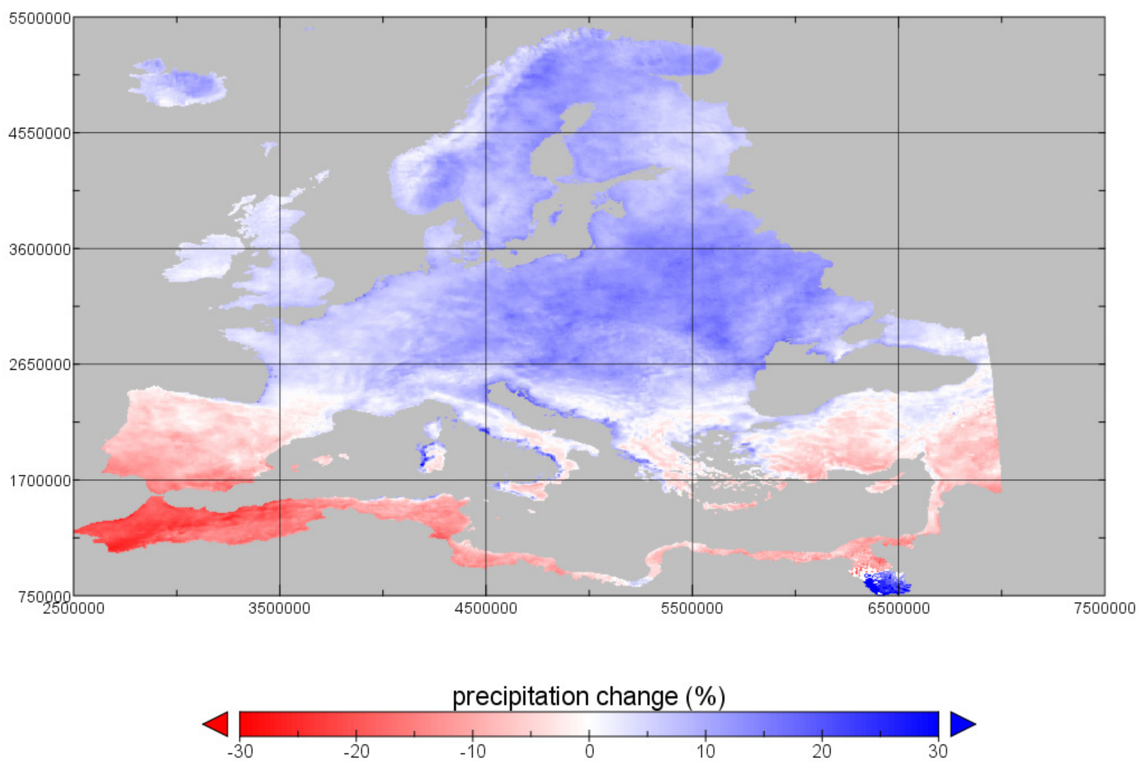

Figure 11 Projected annual average precipitation changes in Europe at the time when a global average temperature of 2 degrees is reached (average of 11 Euro-Cordex models).

5 The LUISA land use projections for Europe until 2050

For this study, the LUISA reference land use projections 2010-2050 have been used in LISFLOOD as well as land use input, and as a driver of water demand as well. They will be described below. While LUISA is typically covering EU28 only, specifically for the Danube region, additional data were collected for Serbia, Bosnia-Herzegovina, and Montenegro, to include these countries as well. This allowed a completer picture of the Danube water resources, which is relevant at European scale as well. For other countries, land use projections were not available, and land use and water demand have been kept constant throughout the simulations.

5.1 The LUISA platform

The future land use projections used in this study are modelled using the JRC LUISA Territorial Modelling Platform. The LUISA platform is developed to satisfy the EC's growing need for an instrument for the ex-ante evaluation of its policies from a holistic perspective; thus, by taking into account the economic, social and environmental effects of those policies. The LUISA platform consists of dynamically interlinked models that are tasked with the computation of regional future land demand, accessibility levels, population distribution, land-use patterns and sustainability-related indicators. Next to a wide range of indicators, key outputs of the LUISA platform are fine resolution maps (100m x 100m grid cells) of accessibility, population densities and land-use patterns for each of the model's time steps covering all 28 EU member states. In this section the land demand and land-use pattern aspects of the model will be briefly described, after which some of the results relevant for this report will be shown.

All results in the LUISA platform are governed by estimates of regional future land demand that are the direct or indirect results of various sectoral models. Those expected regional demands are fed into the LUISA platform with in the case of expected land demand a short bandwidth of acceptable deviations from the input model. These land demands form fixed constraints for the area of land that the population and land-use models in LUISA may assign while running. Relevant regional inputs are Eurostat for population projections (EUROPOP 2011 scenario); GEM-E3 for economic projections; the CAPRI model for projections of agricultural land demand (PRIMESCOR scenario); and UNFCC for projections of changes in forested areas. The latter are based on trends of afforestation/deforestation that are obtained from national counts of forest area as declared to the UNFCC. In some cases additional data are used to obtain land demands from the specialised model outputs. For instance, GEM-E3 delivers estimates of future GDP. Those estimates are translated into expected demand for industrial areas by exploiting data on historical industrial land-use intensities. The mechanisms to obtain land-use demands from various specialised models are described in Baranzelli et al. (2014) and Jacobs et al. (2017).

As noted before the input population numbers and land demands are constraints for the LUISA modules that manage the spatial distribution of people and land-use patterns. Because in particular land-use patterns are relevant for the subject of this report, we will focus on the modelling of those land-use patterns here. For a description of the population allocation module we refer to (Batista e Silva et al., 2013). The land-use allocation module distributes discrete land-use classes by simulating competition between the modelled land-uses. Its core was initially based on the Land Use Scanner (Hilferink and Rietveld, 1999) (Koomen et al., 2011), CLUE and Dyna-CLUE (Verburg and Overmars, 2009; Verburg et al., 2002) land-use models (Verburg and Overmars, 2009; Verburg et al., 2002), but has since been substantially modified to allow for interactions with the population allocation and accessibility modules. The land-use allocation module assumes that land-uses attempt to achieve most attractive locations through a bidding process. For each land-use, total regional areas are limited by the demand for the land use as well as the supply of land in the region. The attractiveness of locations is defined through potential accessibility, exogenous variables such as slope and distance to roads, neighbourhood relations, expected policy effects and a-priori defined costs involved in the transition from one land use to another.

LISFLOOD (5km resolution) integrates future land-use patterns on a substantially coarser spatial and thematic resolution than the LUISA platform output data (100m resolution). To deal with this resolution difference, LISFLOOD uses the fractions of landuse within a 5x5km pixel. Like this, details of the 100x100m level will remain for a large part. Like this e.g. changes in urban coverage from 2% to 3% within a 5x5km area are still taken into account. For a complete description of the LUISA modelling platform and its underlying mechanics we refer to (Batista e Silva et al., 2013; Lavalle et al., 2011).

5.2 Population and GDP projections for Europe

As noted before the input population numbers and socio-economic projections are constraints for the LUISA model (Batista e Silva et al., 2013). Relevant regional inputs are Eurostat for population projections (EUROPOP 2011 scenario) and GEM-E3 for economic projections.

National demographic projection numbers are further downscaled to achieve a higher spatial granularity, resulting in the projected spatial changes in population between 2010 and 2050 as shown in Figure 12 below.

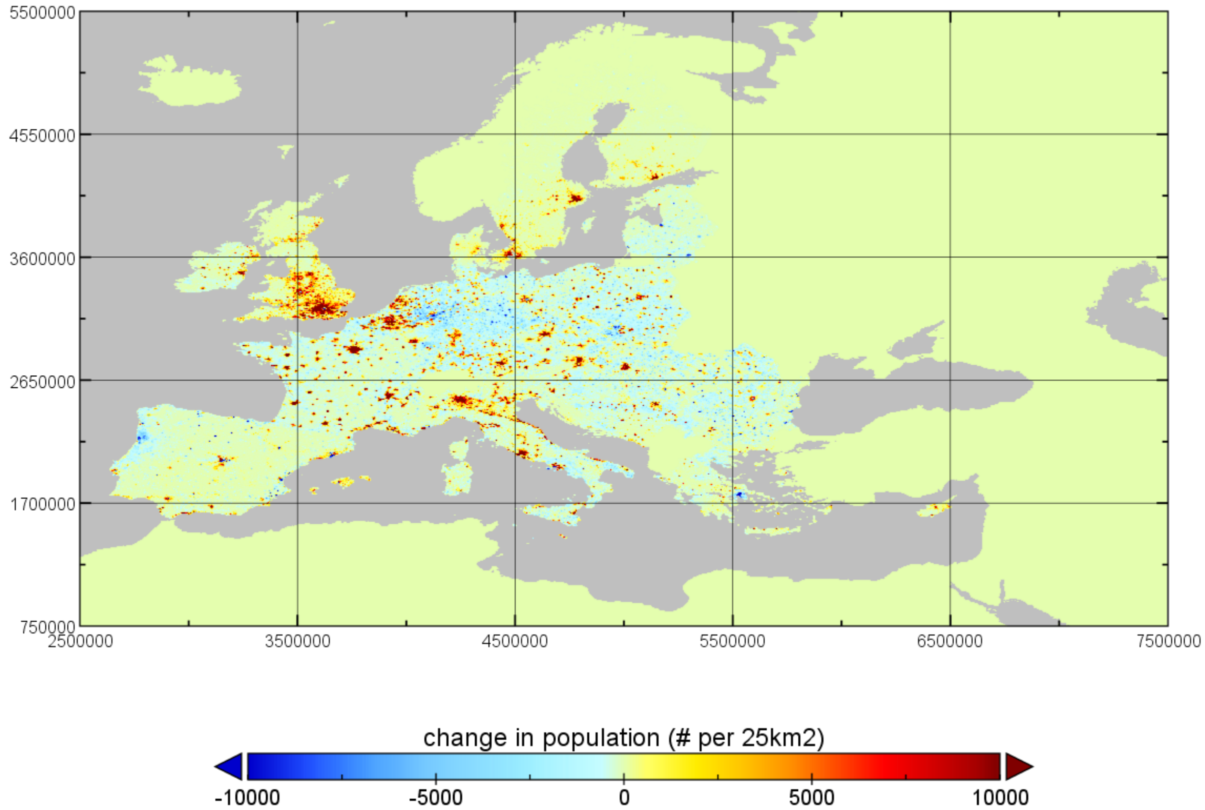

Figure 12 Population change between 2050 and 2010, used to drive the LUISA reference scenario (Source: Europop 2011).

The projections show an overall decrease in rural population, while a net increase is projected for major urban areas – in particular capital cities. Patterns of depopulation are particularly pronounced in areas with low accessibility and lack of economic opportunities. These effects are common (although at various magnitude levels) to all examined countries.

Economic projections are also an important input for LUISA land use projections. We used the GEM-E3 results for the projected growth of the Gross Domestic Product (GDP), which is then also used to make projections of future water demand which are linked to GDP changes.

5.3 Projected land use changes for Europe

For the land use changes in this project, we have used the fractions of the seven main land use classes from 2010 until 2050: sealed areas, forest, rainfed arable land, open water, irrigated arable land, paddy rice irrigated areas, and other vegetation. LUISA simulates more detailed land use classes, but for the use in LISFLOOD, some of the classes are merged.

In line with the demographic trends, the areas with sealed surfaces are projected to increase in urbanised areas mainly, with hardly any changes elsewhere (figure 13)

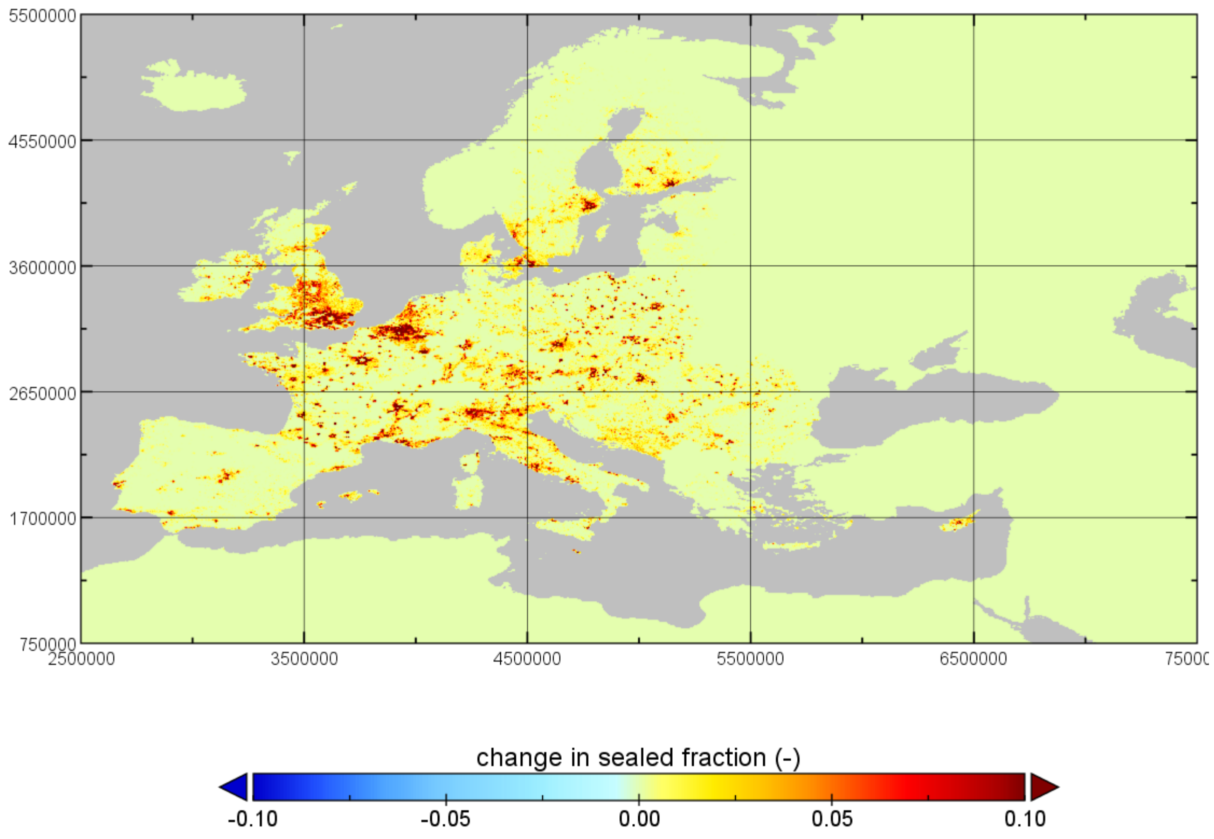

Figure 13 Change in sealed area fraction between 2050 and 2010, LUISA reference scenario.

Increases of around 10% in urban land use are projected in several parts of Europe, and typical in already urbanised areas such as Southern England, Milan, the Benelux countries, Paris, Stockholm etc.

Projections of forested areas do vary from one EU member state to another (figure 14).

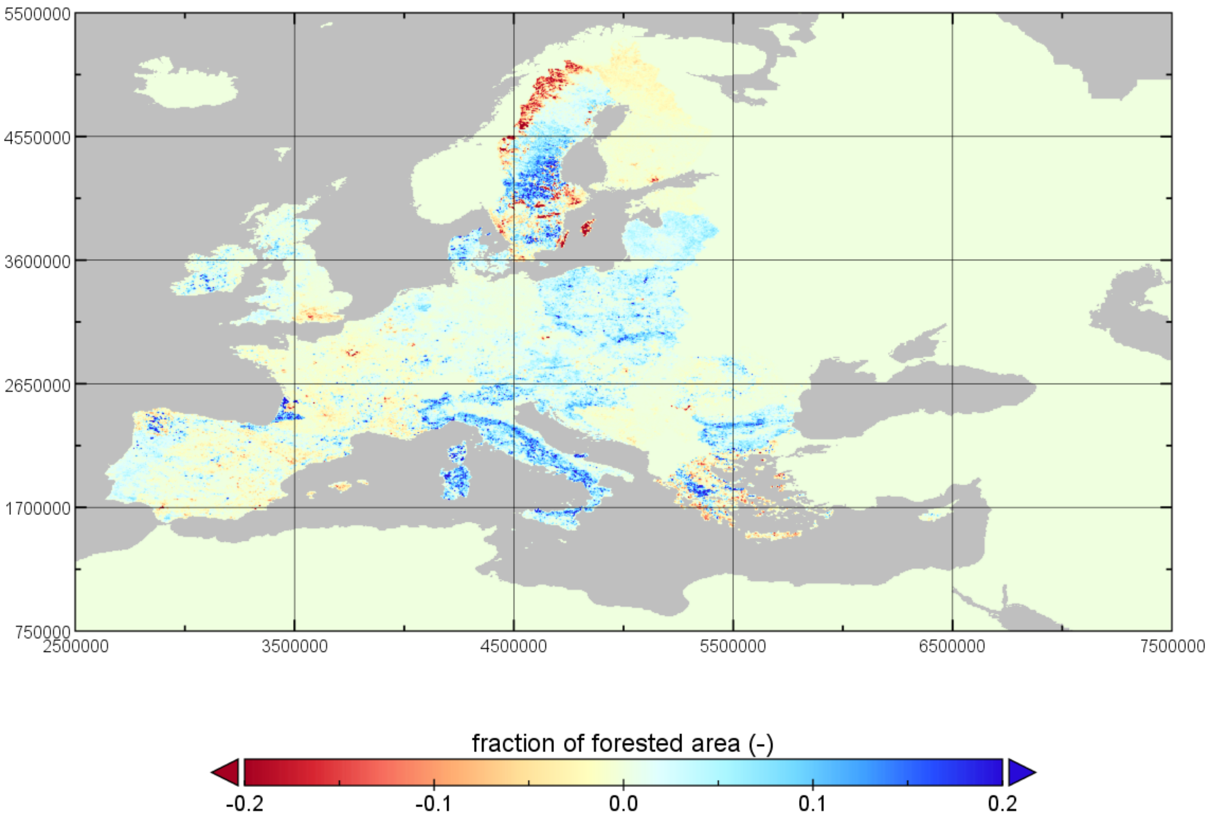

Figure 14 Change in forested area fraction between 2050 and 2010, LUISA reference scenario.

The land use trends are the consequence of the socio-economic patterns previously illustrated. Depopulation fosters the abandonment of agricultural sites and the shrinking of small towns in rural areas. This trend is somehow compensated by the increase of urban land, driven by internal migration processes. It is worth specifying that the term ‘urban land’ in this context refers to artificial areas – hence its increase does not necessarily correspond to complete urbanisation processes resulting in new cities or towns.

6 Changes in water demand and consumption until 2050

Water demand is typically broken down into five components: domestic water demand, (manufacturing) industrial water demand, water demand for energy and cooling, irrigation water demand, and livestock water demand. Irrigation demand is estimated dynamically within the LISFLOOD model – because it is driven by climate conditions -, whereas the other components are external input data. These five water demand components are described below.

6.1 Irrigation simulation in LISFLOOD 2.0

Within LISFLOOD version 2, irrigation water demand is dynamically simulated since it depends on climatic conditions. Within LISFLOOD, a distinction in simulation methods is used for crop irrigation and paddy-rice irrigation. Crop irrigation is simulated using the evaporative demand of the crop. That demanded water amount by the crop is compared to the available water in the soil. The model aims to keep the soil at field capacity soil moisture content (pF 2.0). The potential lack of water is then used to define the irrigation demand. In addition, a locally specific irrigation efficiency can be defined, to distinguish e.g. drip irrigation from sprinkler irrigation typically adding 10-40% water beyond the net crop demand. Also conveyance losses are taken into account by a user-defined percentage, thus adding another 0-20% to the water demand. Finally, a 'safety margin' amount can be included, for example with the aim to prevent salination of the soil by irrigation too tightly.

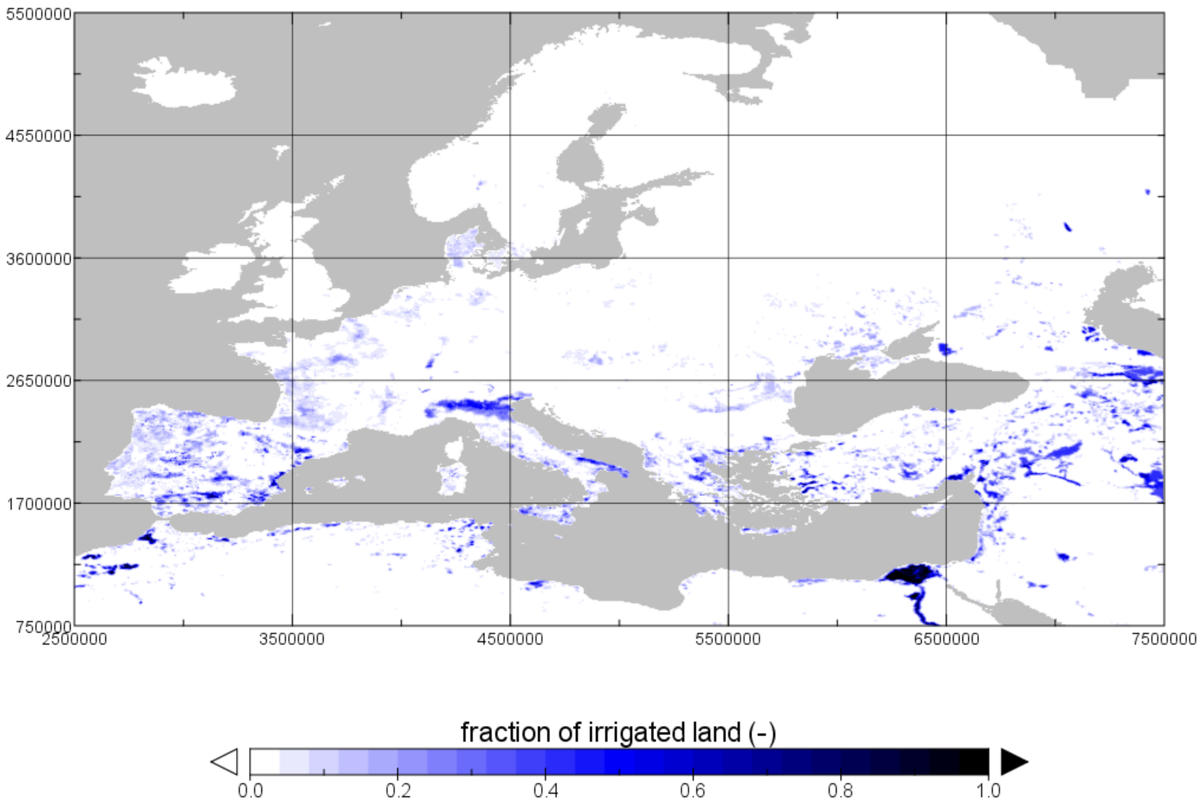

Figure 15 Fraction of irrigated areas (within a 5x5 km model pixel), valid for 2010 (Source JRC: Wriedt et al, 2009).

Paddy rice irrigation is simulated in LISFLOOD by first of all defining a planting and a harvest date in the year. Ten days prior to the planting, a user-defined water level is set on the rice field (typically 5-10 cm total) during 10 days, thus adding 5-10 mm water every day. Until 20 days before harvesting, this water level is maintained constant, by applying daily an amount of water equal to the open water evaporation of that particular day on that particular location. Twenty days before harvesting, no more water is applied and the rice field is drained. Additionally, water losses due to soil percolation can be user-defined (typically ~2mm/day). LISFLOOD can also simulate a 2nd rice harvest if appropriate.

6.2 Water demand and consumption of the other sectors

In general, water use estimates for these four sectors are derived from mainly country-level EUROSTAT data with different modelling and downscaling techniques as described in Vandecasteele et al. (2014). Downscaling of national values to higher spatial detail is important, because water use is distributed heterogeneously across countries with high values in concentrated areas with high population density or industrial plants. Land use maps by the LUISA platform are used to ensure consistency with European policies and scenario assumptions. In areas are not covered by LUISA (e.g. Ukraine), Corine land use maps are used for spatial downscaling. Temporal trends of future water use are modelled using projection scenarios consistent with those used by the LUISA platform, such as GEM-E3 for economic projections and EUROPOP for population projections. Within the LISFLOOD model, water demand is used as input data (figure 16). Per sector, water consumption factors (table 2) are used and applied to calculate return flow and net water consumption.

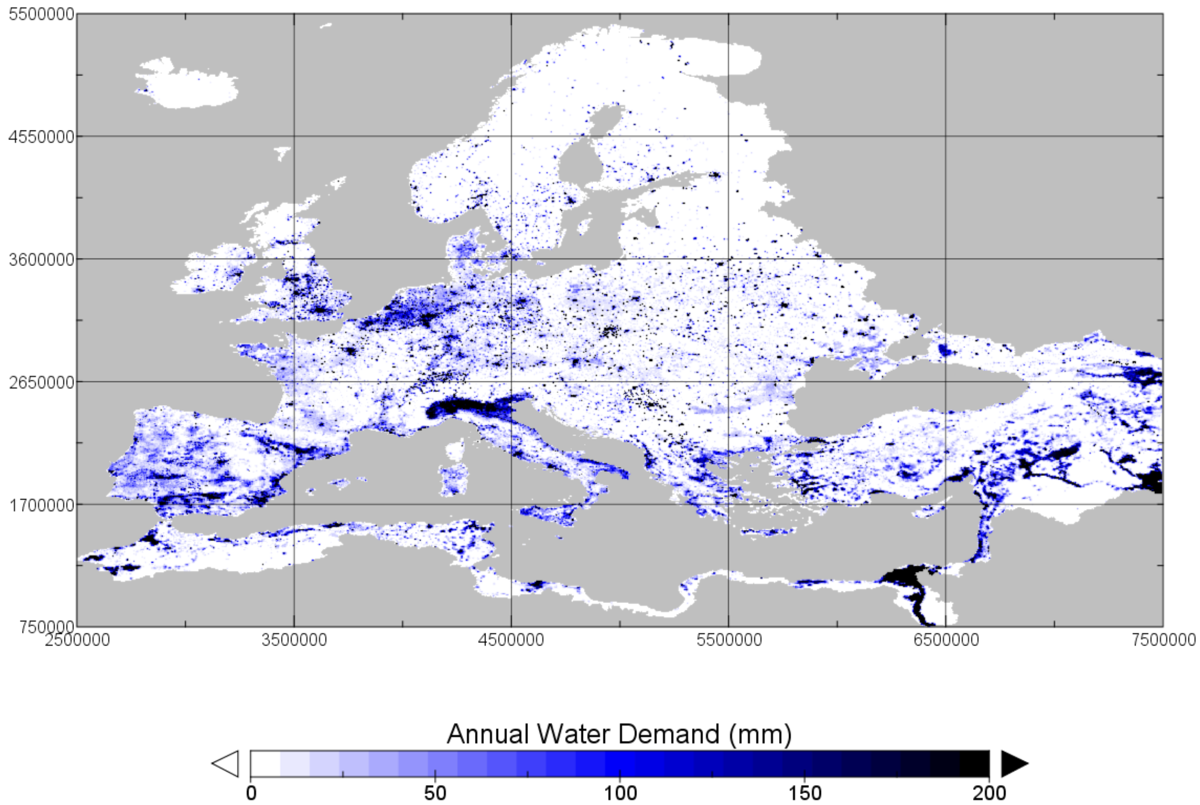

Figure 16 Annual water demand from all sectors, including irrigation (mm), as estimated in this study for the reference period 1990-2016.

Industrial water demands are based on country-level figures from national statistics offices for the total water use by manufacturing industries, mining and construction. The national water use data are mainly originating from EUROSTAT and AQUASTAT, complemented with additional work of Bernhard et al. (2018a). Future industrial water use trends are simulated based on GVA (Gross Value Added) projections to represent industrial activity and an efficiency factor to represent improving water efficiency due to technical developments. The GVA projections are available from the GEM-E3 model at NUTS-2 level with five year intervals and linear growth is assumed between those years. The efficiency factor assumes a decrease in water use by industries of 1% per year (assuming constant GVA), based on analyses of historical trends (Bernhard et al. 2018b, Flörke et al. 2013). Subsequently, the national totals are disaggregated to the industrial land use class of the LUISA platform to obtain spatially downscaled water use estimates per 5 km grid cell. Since the GEM-E3 model only provide projections for the EU28, industrial water use projections are assumed constant for countries outside EU28.

Water demand for energy and cooling is computed with a relatively similar approach as industrial water demand above. National water use statistics from EUROSTAT or AQUASTAT are downscaled to the locations of large power thermal power stations registered in the European Pollutant Release and Transfer Register data base (E-PRTR). Subsequently, the temporal trend of energy water use is simulated based on electricity consumption projections from the POLES model (Prospective Outlook on Long-term Energy Systems, JRC).

Livestock water withdrawals are estimated by combining water requirements from literature with livestock density maps for cattle, pigs, poultry, sheep and goats (Mubareka et al., 2013). FAO livestock density maps (FAO, 2012) are refined with actual livestock figures for 2005 (CAPRI, 2012). The methods are described in detail by Mubareka et al. (2013).

Table 2 Consumptive use percentages used in this study to split water abstraction into net water consumption and return flow. Note: if spatial/country specific information would be available, LISFLOOD could be run with spatially specific maps of these coefficients

SECTOR	**Consumptive use (%)**
Household water	20%
Manufacturing industry	15%
Energy & cooling (source: Torcellini et al. 2003)	33% near open water (large rivers, lakes, coast) 2.5% in other areas
Livestock	15%
Leakage of public water supply network	20%
Irrigation efficiency	75%
Conveyance efficiency	80%
Irrigation Safety Margin	20%

Water demands for the household sector are derived from a specific household water usage module (Bernhard, in prep.) which simulates water use per capita based on socio-economic, demographic and climate variables. This model was based on collected data at NUTS-3 level (over 1200 regions in Europe) from 2000-2013 for all EU28 countries on household water use, water price, income, age distribution (fraction of population aged below 15) and number of dry days per year. Subsequently, regression models were fitted to quantify relationships between water use, water price and the other relevant variables for four European clusters of NUTS-3 regions with similar socio-economic and climate conditions. This model allows to estimate present and future domestic water use per capita at NUTS-3 levels using scenario projections for the socio-economic (GEM-E3), demographic (EUROPOP) and climate (CORDEX) variables.

Due to the lack of data on regional water prices and other relevant variables, it is not possible to expand the model outside EU28 countries. Where possible, the 2010 map is constructed with regional values of water use per capita and otherwise this is complemented with EUROSTAT data or the EU-average. The regional water use per capita values are multiplied with detailed population maps from the LUISA platform to obtain domestic water use maps from 2010 up to 2050 for every 5 years. For the years in between the 5yr-window a linear growth is assumed.

Consumptive use for the domestic sector is assumed at 20% (EEA 2005) (table 2), meaning that 80% flows back in the hydrological system as waste water.

Leakage of water from the public supply network is also simulated. For simplicity reasons, we have assumed that there is a 20% leakage from the supply network. Better national scale data on leakage became available only after the start of this modelling work.

6.3 Water demand and consumption projections until 2050

Figure 17 shows a map of the projected change in total water demand between 2010 and 2050 for all water usages excluding irrigated agriculture. Irrigation is simulated dynamically in each single LISFLOOD run depending on the climatic forcing and land use and crop patterns. Thus, the model will react during warm dry summers by trying to abstract more water for irrigation to compensate the lack of soil moisture.

In general, the total water demand change is following the spatial distribution of the urban land use increase with an increase in total water demand in urban areas. These are typically also the areas with industries, which may have an increasing water demand.

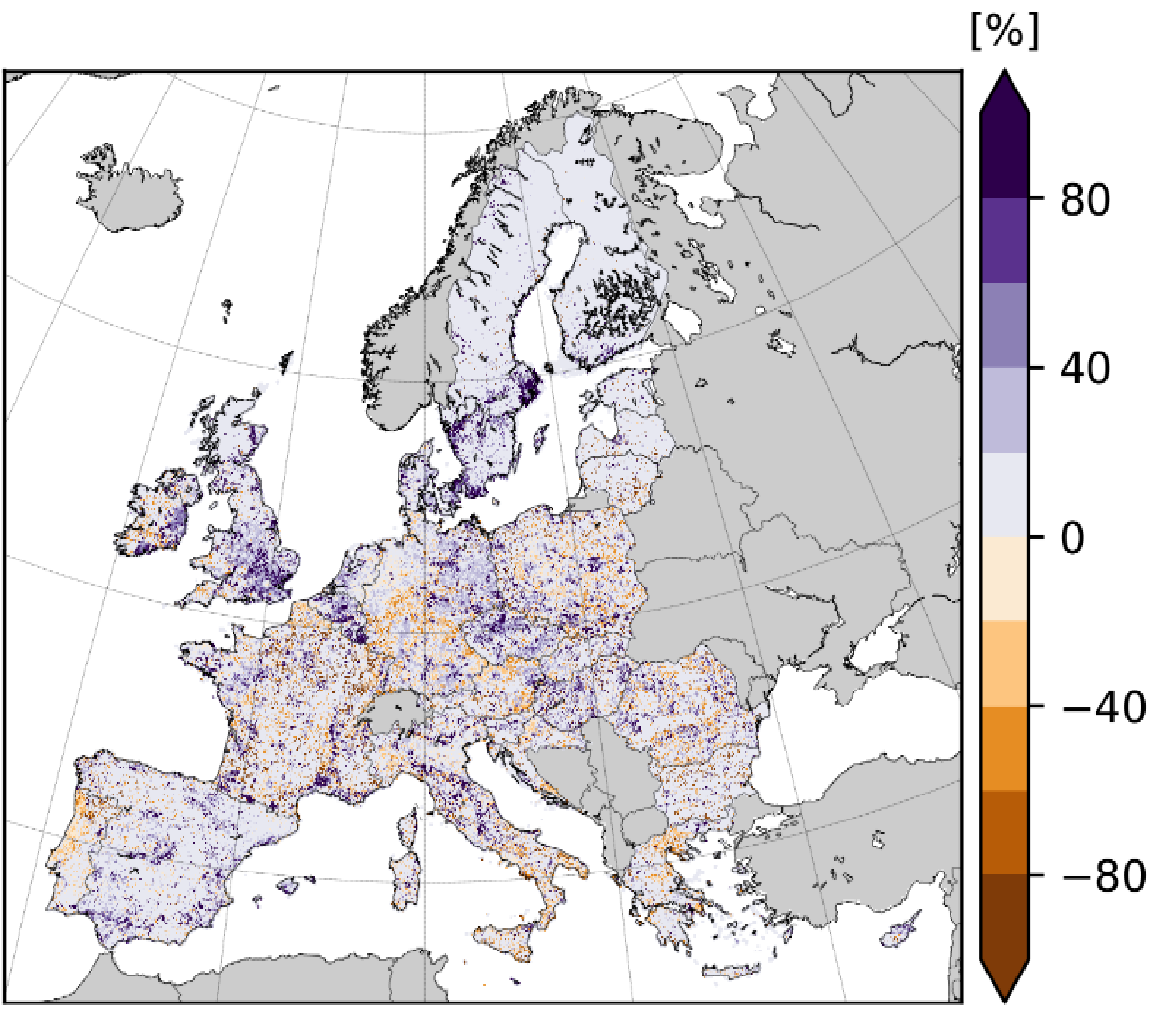

Figure 17 Projected changes in water demand by 2050 as compared to 2010, for all sectors except irrigation. These changes are due to projected population, GDP and GVA changes mainly. Source: JRC 2018.

In this study we use the Water Exploitation Index to demonstrate the balance between water demand and availability. The WEI-demand index is the ratio between water demand in a region, and the water availability in a region. In a changed Europe, both water demand and availability are changing dynamically in space and time. Water demand is changing due to land use, economic, population, and climate changes: people tend to consume more water if it is warmer, and if they are wealthier. Water availability is changing due to the projected climate changes.

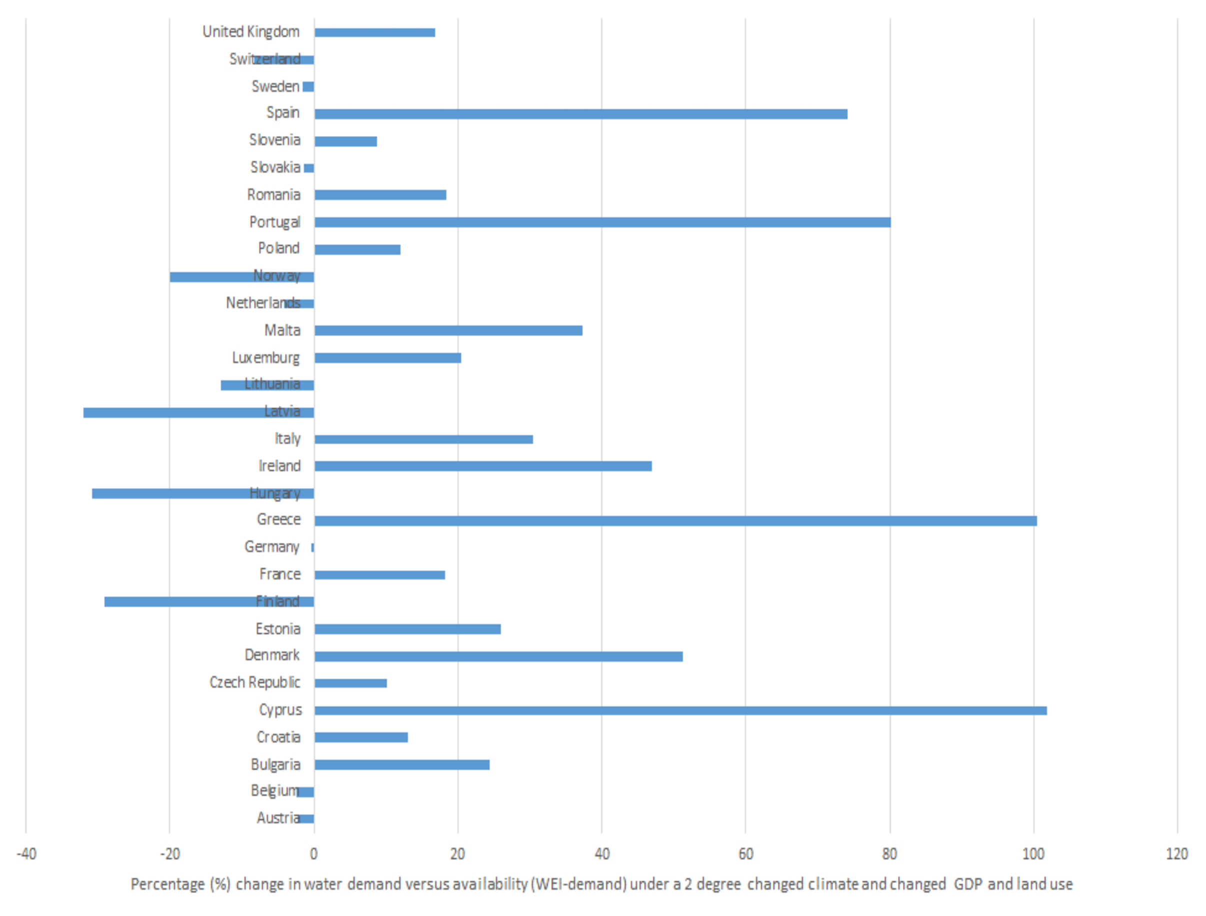

Figure 18 Percentage change in the average water demand-availability ratio (WEI) per country under a 2 degree climate versus current climate. Also LUISA projected land use changes and GDP changes are taken into account in the water resources modelling and estimations of future water demand.

Figure 18 shows increased pressures of 20% or more on future water resources in Spain, Portugal, Malta, Italy, Ireland, Greece, Estonia, Denmark, Cyprus and Bulgaria. This is increased pressure is a combination of changing water demands and changing water supply. So even when the demand goes down, the pressure could increase if the availability decreases even more.

7 Impacts of climate, land use and water demand change on water resources in Europe

This chapter describes the results of the water resources calculations obtained with the LISFLOOD model. In total 22 model simulations with the LISFLOOD water resource model for 30-90 year periods including climate, land use and water demand changes have been evaluated for their impact on European water resources.

In the next paragraphs, we describe the impacts of changing climate, land use and water demand on water resources for various aspects such as water scarcity, high flows, low flows, soil moisture, groundwater, hydropower, cooling, and the impact on urban areas.

7.1 Impact on annual and seasonal streamflow and water availability

First we evaluate the annual and seasonal overall water availability, and how this is projected to change in the future.

The results of the water resources impact simulation under a 2°C warming scenario, including CC, LU and WD projections (total change) show a North-South pattern across Europe for water availability (figure 19).

Overall, Southern European countries are projected to face decreasing water availability, particularly Spain, Portugal, Greece, Cyprus, Malta, Italy and Turkey. Central and Northern European countries show an increasing annual water availability

Figure 20 shows that the extremer RCP8.5 2070-2099 warming scenario displays the same spatial pattern as under the 2°C warming scenario, but more extreme in the amounts of increasing and decreasing water availability

Seasonal changes are shown in figures 21 (2 degree warming) and 22 (extreme warming) - show a more nuanced picture, with marked differences between summer and winter streamflows, especially in France, Belgium and the UK. These 3 countries are projected to experience wetter winters and drier summers, with increased water availability in winter, and decreased water availability over the summer months.

The extremer RCP8.5 2070-2099 warming scenario displays again a more pronounced seasonal change of water availability (figure 22) It shows the same spatial pattern as under the 2°C warming scenario, but more extreme in the amounts of increasing and decreasing water availability

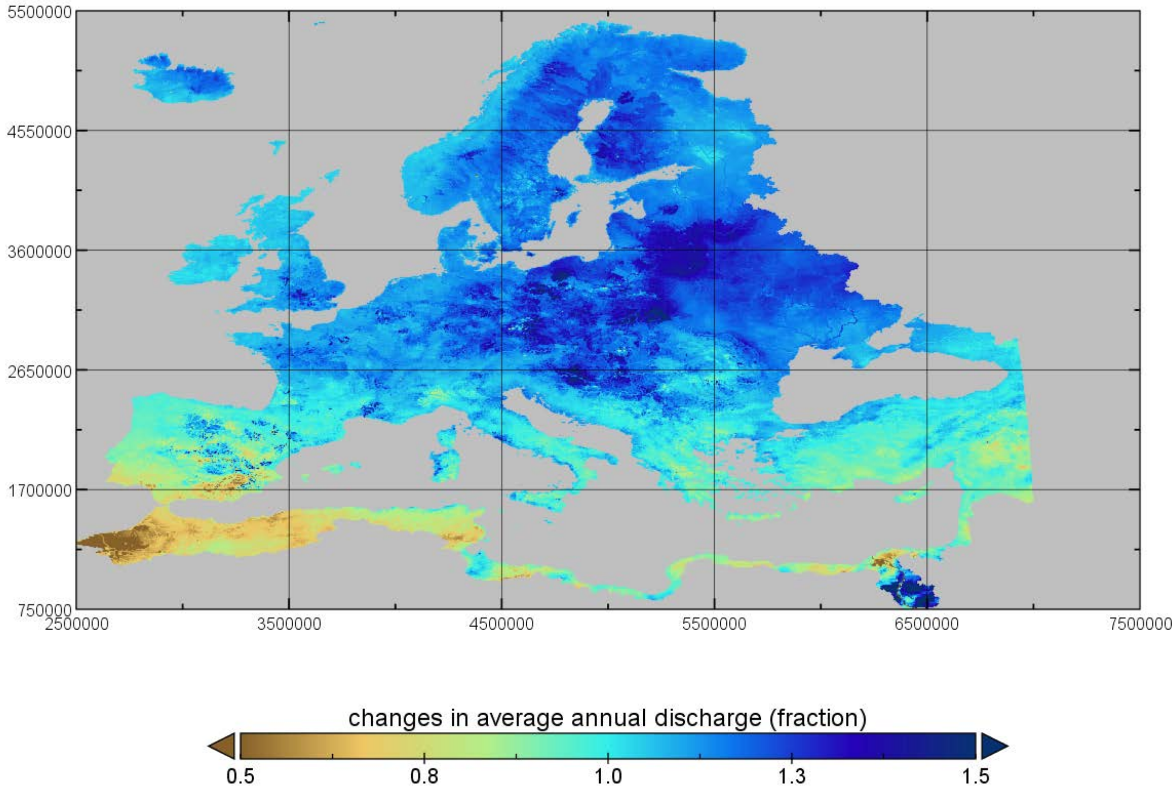

Figure 19 Changes in average streamflow for the 2degree changed climate compared to the 1981-2010 control climate ('hist'): values above 1 indicate increases in streamflow and water availability, values below 1 indicate decreases.

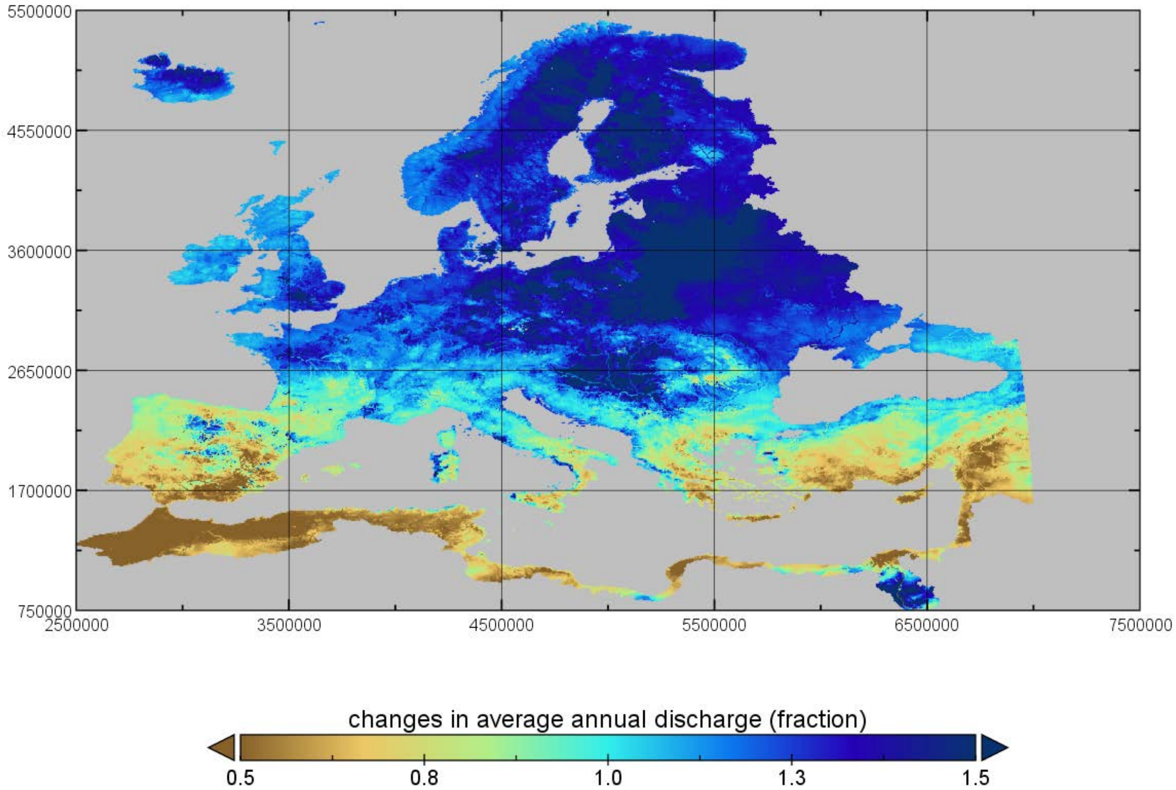

Figure 20 Changes in average streamflow for the RCP8.5 2070-2099 climate compared to the 1981-2010 control climate (hist): values above 1 indicate increases in streamflow and water availability, values below 1 indicate decreases.

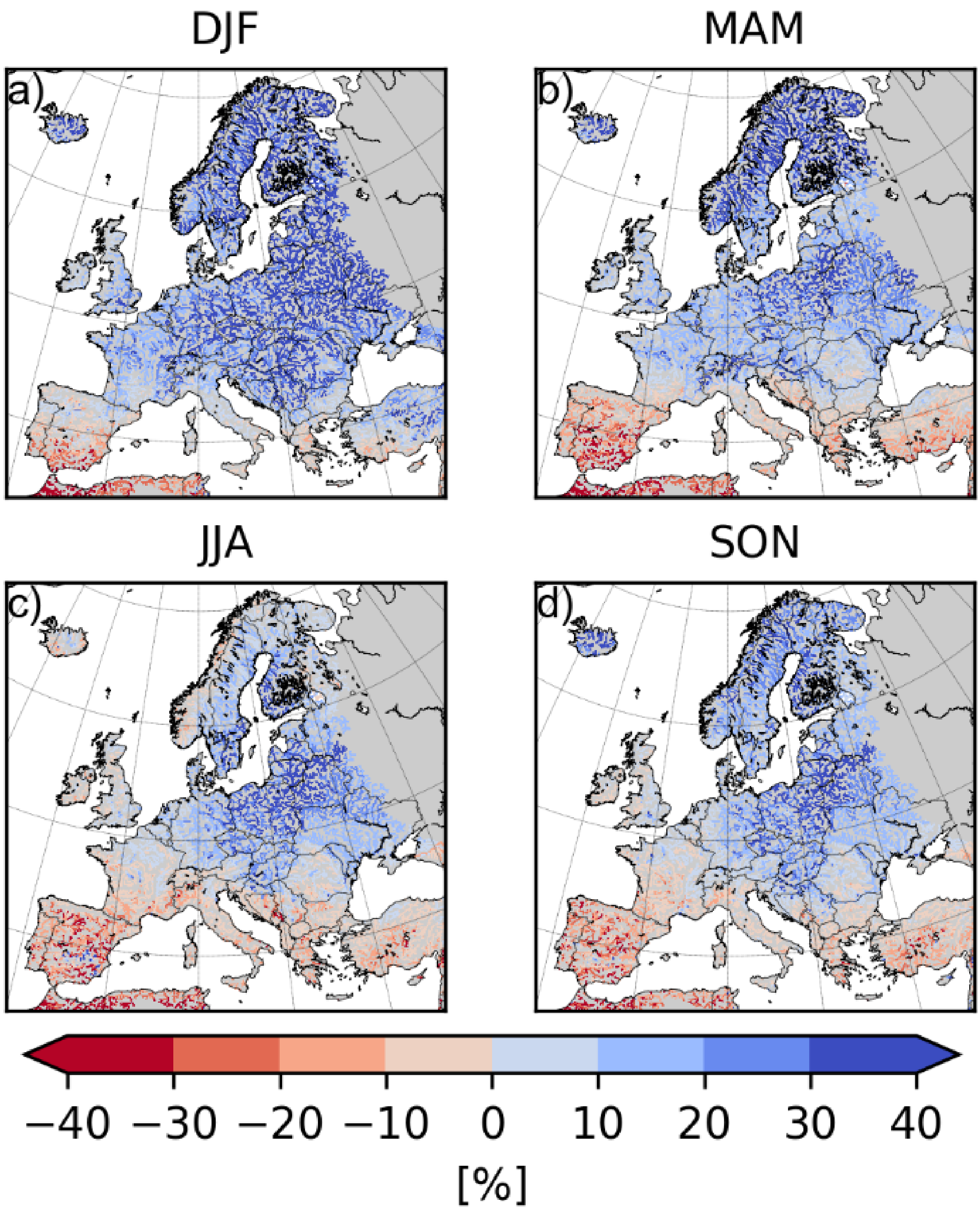

Figure 21 Impact of 2 degree climate change on median seasonal streamflow (50^{th} percentile), as compared to the 1981-2010 control climate, showing the combined effect of climate change (CC), land use change (LU) and water demand change (WD).

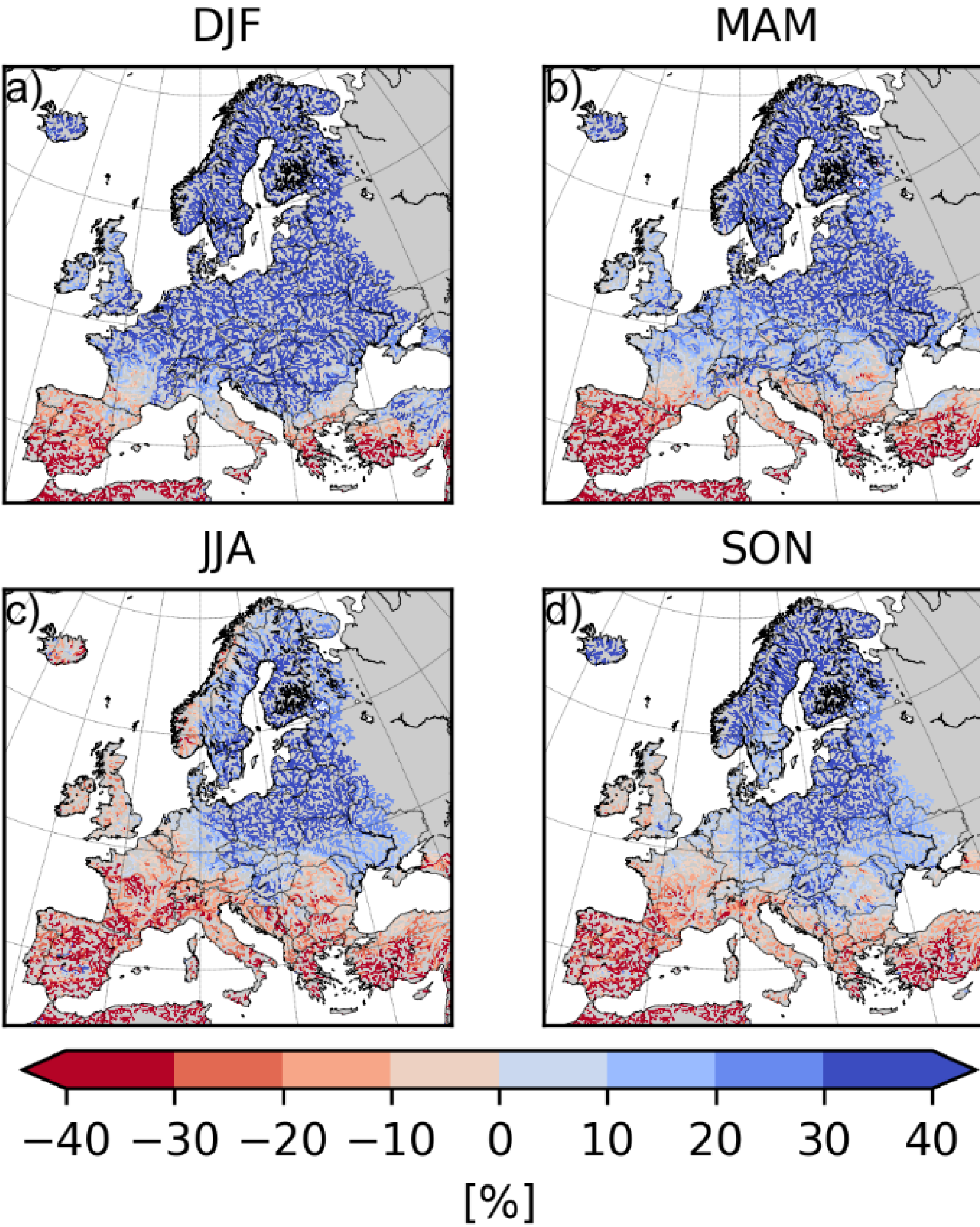

Figure 22 Impact of the RCP8.5-2070-2099 climate change on median seasonal streamflow streamflow (50th percentile), as compared to the 1981-2010 control climate.

In a recent study for the Danube river basin (Bisselink et al., 2018) we specifically analysed the individual contributions from climate, land use, and water demand to the projected changes (figure 23). What we found is that the projected changes in climate are by far the dominating factor of changing water resources. The contribution of land use changes and water demand changes combined are in the order of 10-20%, whereas climate is responsible for 80-90% of the projected changes.

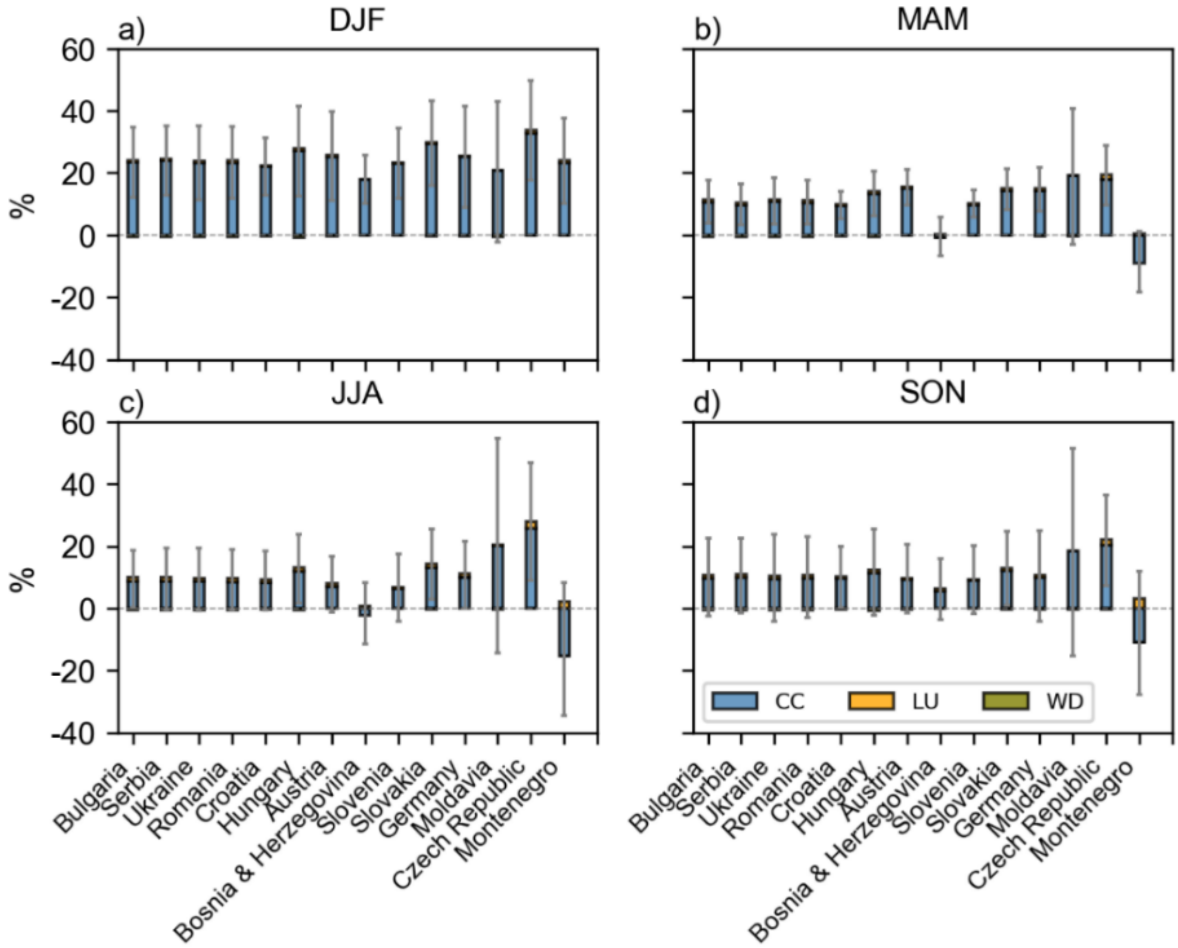

Figure 23 Average streamflow change per Danube country under 2 degree climate change as compared to the 1981-2010 control climate, showing the combined effect of climate change (CC), land use change (LU) and water demand change (WD). Note: vertical bars represent the standard deviation of the total change.

7.2 Impact on high flows

Floods are of major concern in Europe. Previous studies on climate change effects already mentioned projections of increased flooding in Europe (Dankers & Feyen, 2008; Dankers & Feyen, 2009).

In this study, we examine the 99.5th percentile of streamflow as an indicator for high flows. The 99.5th percentile of daily flows is more or less comparable to a 1-year return period streamflow – so more or less a 'common' high discharge, where normally flood protection structures should be adequate.

Figure 24 shows the projected changes of this high flows under the 2 degree scenario.

For autumn and winter months, the projections indicate increased high flows almost everywhere in Europe, with river discharges at that frequency increasing by 10-30%. Examples of historic floods in the winter months in these regions are the Meuse and Rhine floods of 1993 & 1995.

The springtime months show a decrease in high flows around the Baltic Sea, very likely related to decreasing snow amounts under a warmer climate, and thus less problems with snowmelt floodings

The summer months especially show increased high flows in Central and Eastern Europe. Europe has experienced already a number of extreme summer floods in these regions (Oder, 1997; Elbe & Danube 2002).

Figure 25 shows the projected changes of this 99.5th percentile high flows for the RCP8.5-2070-2099 scenario. Again, the spatial pattern is more or less the same as projected under 2 degree warming, but the magnitudes of the flooding are more extreme.

Mentaschi et al. (2018) are publishing further results related to floods and climate change, based on the same simulation model runs, in a separate publication.

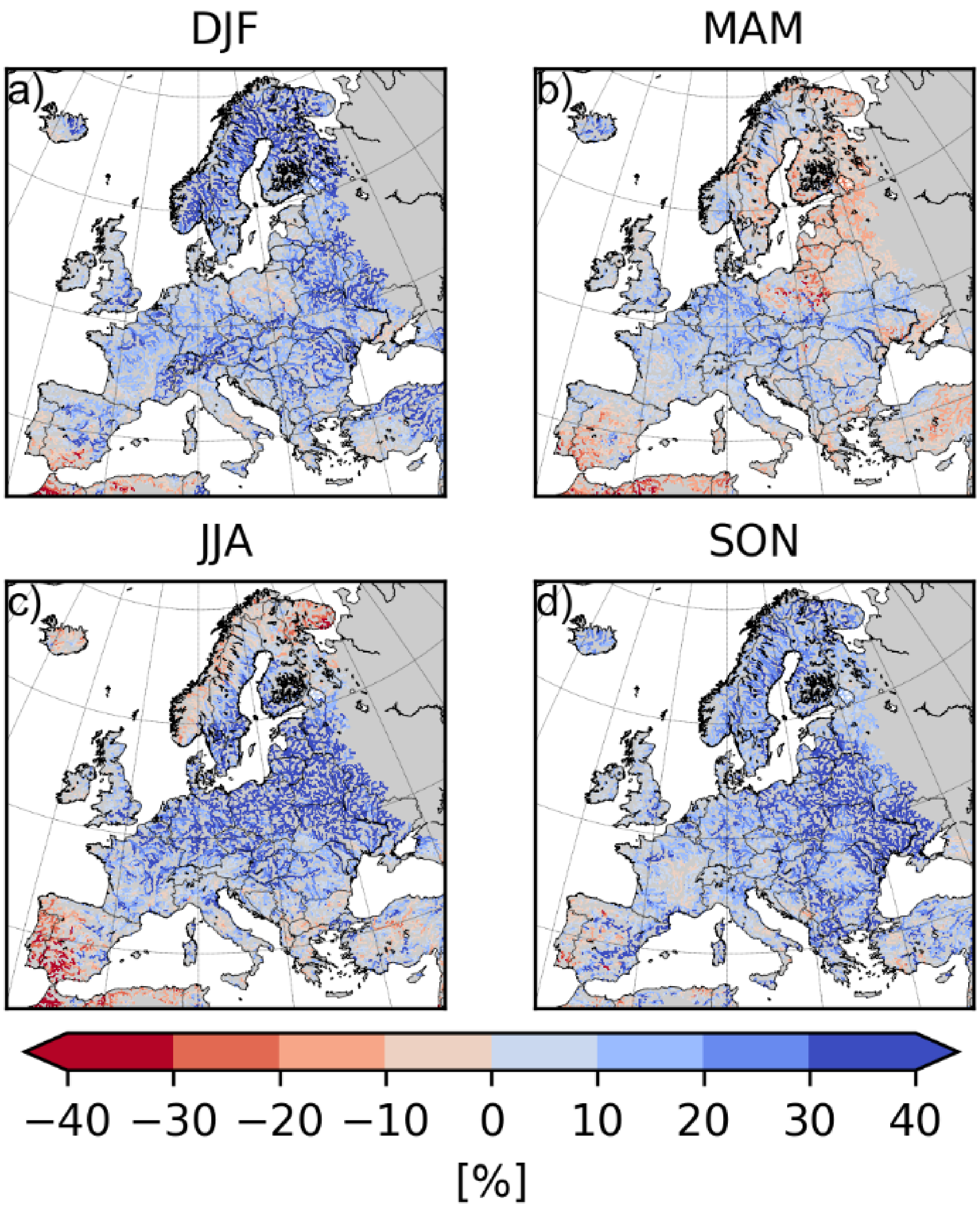

Figure 24 The impact of CC, LU and WD change in a 2 degree climate on high flows, here indicated with the Q99.5: the 99.5 percentile of river discharge, which is close to a 1-year return period flow.

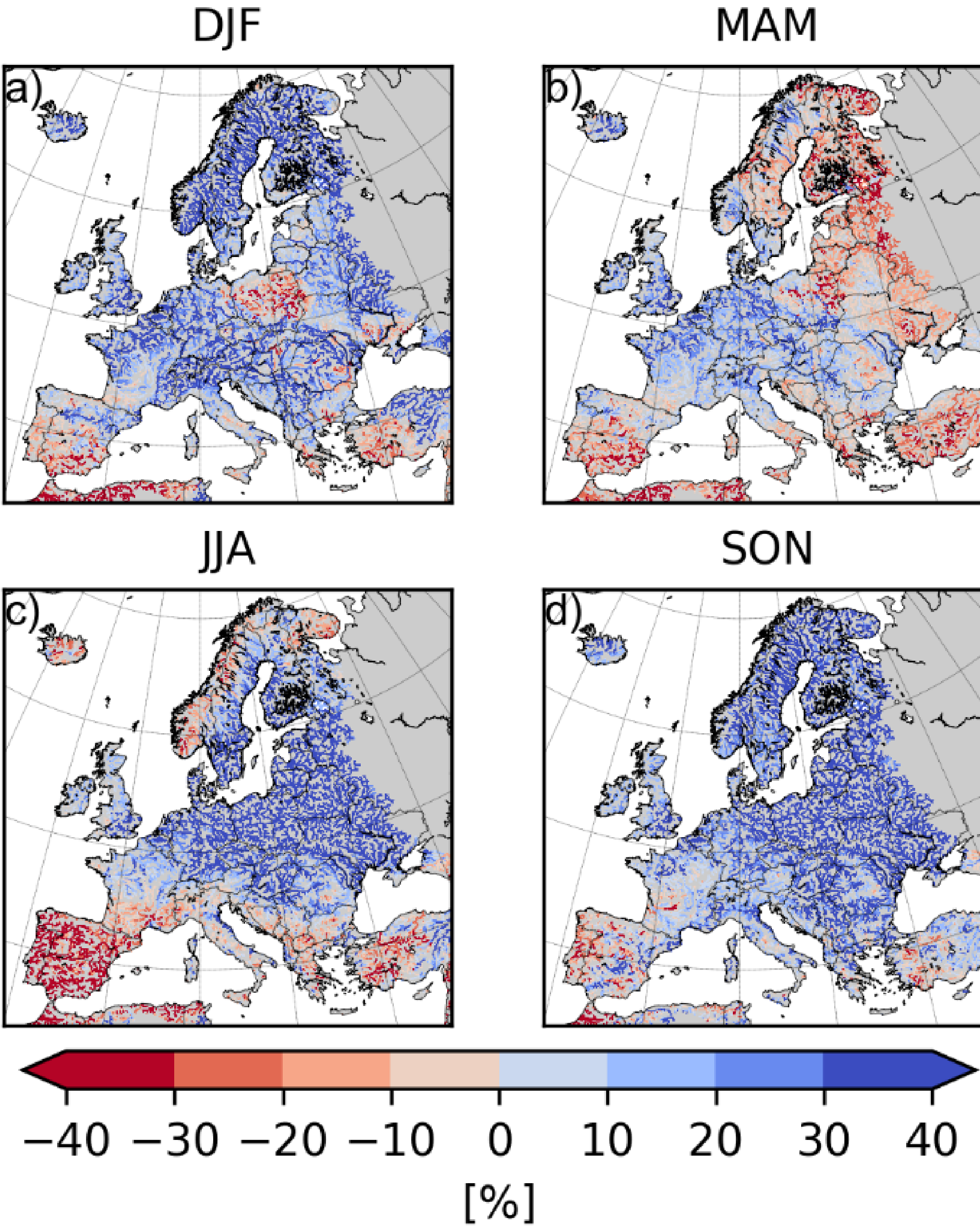

Figure 25 The impact of CC, LU and WD change in an RCP8.5-2070-2099 climate on high flows, here indicated with the Q99.5: the 99.5 percentile of river discharge, which is close to a 1-year return period flow.

7.3 Impact on low flow and navigation

For low flow projections we have taken the Q5 – the 5th percentile of streamflow as an indicator. So this on average corresponding to the 18 days in a year with the lowest river discharge.

The projections for low flow conditions under a 2 degree climate together with projected land use and water demand change (figure 26) for Europe show again the North-South pattern, with typically increased low flow and drought issues in the Mediterranean countries.

Projections for France and the UK show increasing low flow issues as well in the spring and summer season.

The RCP8.5-2070-2099 climate (figure 27) shows again typically the same spatial pattern, but with more extreme magnitudes of wetter and drier conditions.

It should be noted that in this study we have kept the environmental flow constraint very mild (1 m3/s in most rivers), which means abstractions are allowed to continue until that threshold is reached. More stringent eflow thresholds, such as a Q5 or Q10 threshold below which abstraction is not allowed, could lead to different low-flow projections.

Christodoulou et al. (2018) are studying the impacts of climate change on important European inland waterways, the Rhine and the Danube, while using the river discharge simulations of this study. These will be published in a separate publication.

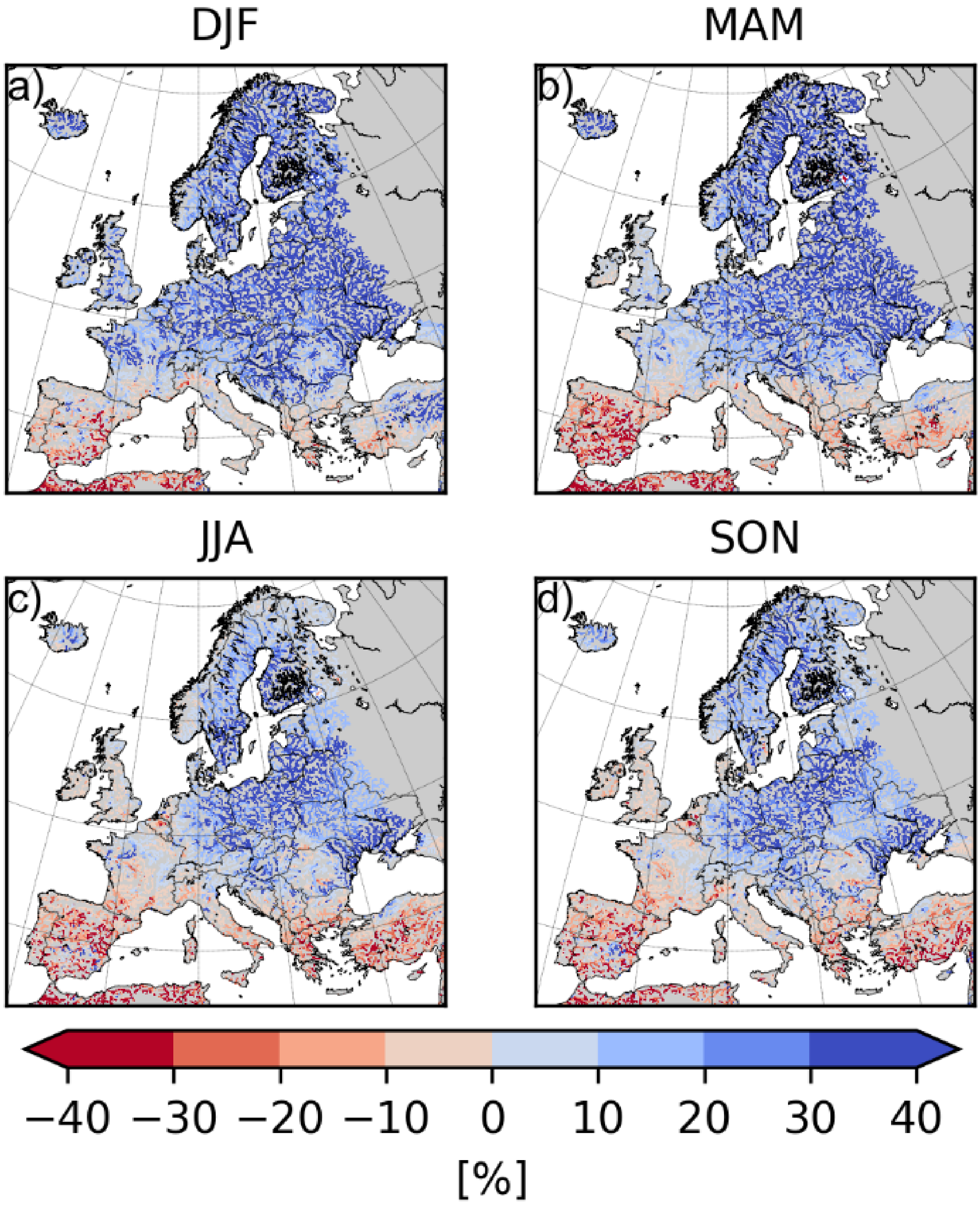

Figure 26 The impact of CC, LU and WD change in a 2 degree climate on low flows, here indicated with the Q5: the 5 percentile of river discharge, which corresponds to flows reached on average around two weeks of the year.

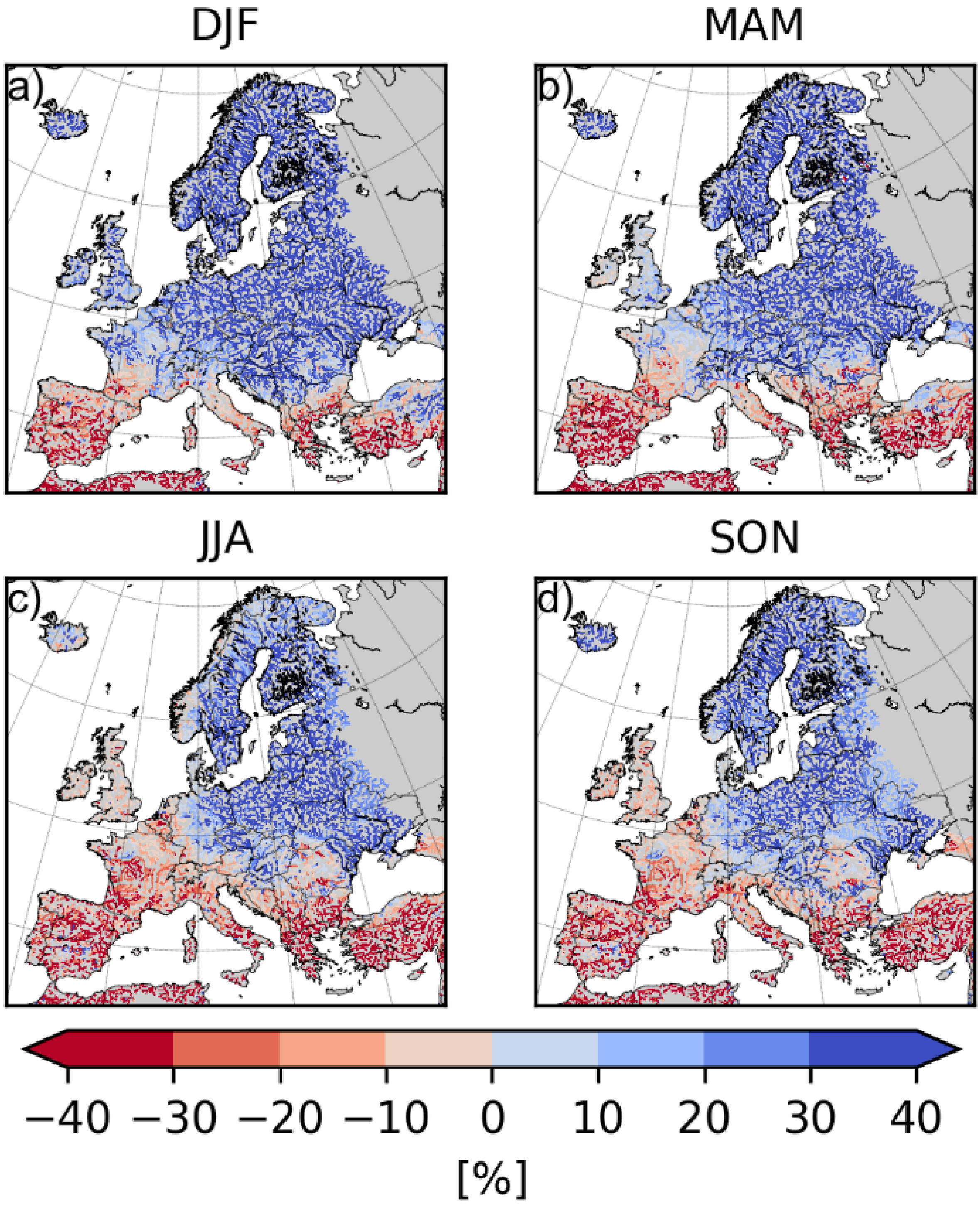

Figure 27 The impact of CC, LU and WD change for the 2070-2099 RCP8.5 climate on low flows, here indicated with the Q5: the 5 percentile of river discharge, which corresponds to flows reached on average around two weeks of the year.

7.4 Impact on water demand versus water availability

To demonstrate the ratio between water demand and consumption versus water availability, we use the Water Exploitation Index Plus (WEI+) (consumption ratio) as an indicator. The WEI+ is defined here as it was discussed in the EU WorkingGroup on Water Scarcity and Droughts around 2011. The WEI+ is defined here as the total water net consumption divided by the freshwater resources of a region, including upstream inflowing water. This definition results in WEI+ values between 0 and 1 (note: the EEA often uses percentages from 0-100%, but the definition is the same).

A WEI using demand or abstraction versus available freshwater resources is typically 2-3 times as high. The difference between WEI+ and WEI is explained by the return flow, resulting from drained irrigation water, (warmed up) cooling water returned to the river, and (treated) wastewater returned to surface waters.

Box 3. Water Regions

The LISFLOOD 2.0 model includes a water abstraction functionality. In similar global water resources models run at 0.5 degree spatial resolution (~50 km) it is typically assumed that the abstraction takes places in the same model grid as where the water demand is.

In a higher resolution model however – LISFLOOD is run at 5km resolution here – this assumption is not valid. The abstraction for a certain activity may well take place tens of kilometres from the activity. Thus, one cannot assume abstraction to take place in the grid where the demand is. Also, this can lead to artefacts of water scarcity. For example large industries or large towns with high water demands would then trigger their own model grid in which they are situated to be water scarce, as likely the demand is higher than the local availability.

There, we have introduced in LISFLOOD 2.0 the concept of ‘water regions’. As we do not know the precise location of the abstraction for a certain activity, we assume the abstraction may well take place in the regional sub-river basin in which the activity is situated. This sub-basin consists then of several individual model pixels. This prevents artefacts of calculating water scarcity that in reality does not exist.

LISFLOOD can simulate with any user-defined water-region map. For this study, we defined water regions as sub-river basins, within a single country: we do not assume cross-border abstractions. In the more recent BLUE2 study, we are using the River Basin Districts as defined under the WFD as water regions.

Abstractions thus take place at regional level, and also water scarcity indicators are then calculated at this regional level.

The WEI+ is calculated and stored for each month within a model run. The WEI needs to be calculated at least at monthly timescale, otherwise a wet winter would compensate a dry summer in the indicator, and one would fail to see a critical water scarce period within a year.

The freshwater resources taken into account to calculate the WEI+ include locally generated runoff and inflowing surface water from upstream countries (e.g. Rhine inflow in the Netherlands), lake and reservoir variable storage, and annual groundwater recharge.

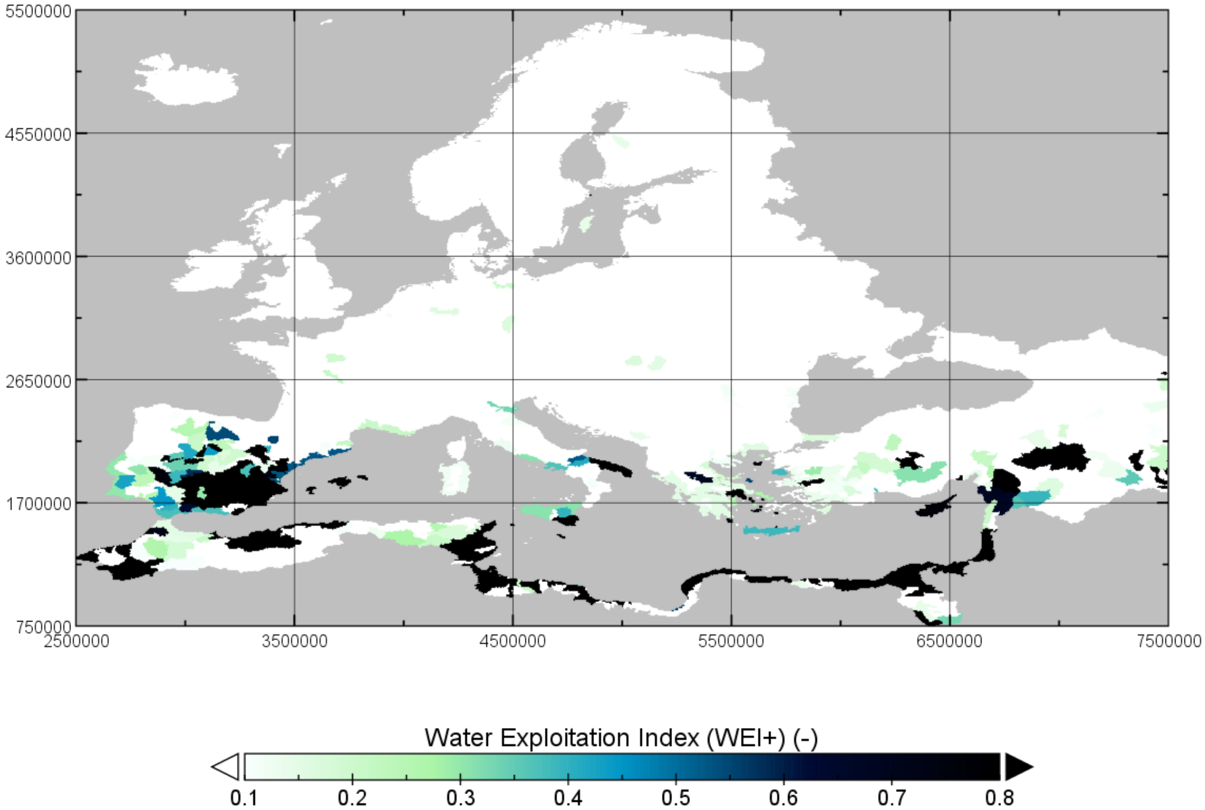

Figure 28 The Water Exploitation Index + (WEI+; net consumption versus availability) for Europe under observed climate (1990-2016).

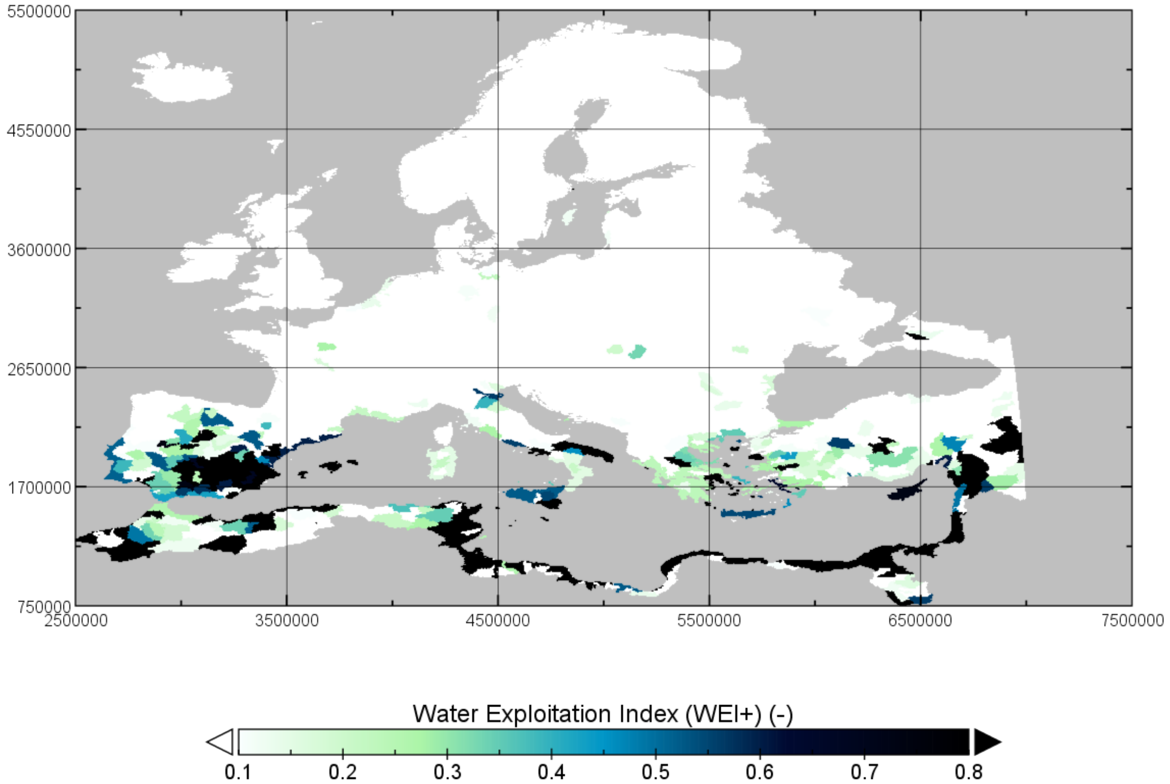

Figure 29 The Water Exploitation Index '+' (WEI+; net consumption versus availability) for Europe under the control climate (1981-2010) (ensemble of the 11 Cordex models). The picture is almost identical to the previous figure using observed meteorological data, meaning that the WEI+ with the climate runs has no bias compared to observed weather.

A high WEI+ index highlights the regions with a net high consumptive use of water. A threshold value for the WEI+ above 0.4 is often used to indicate that a region is severely water scarce. A WEI+ within the range 0.2-0.4 indicates a water scarce region. A WEI+ in the range 0.1-0.2 is classified as moderate water scarce, and a WEI+ lower than 0.1 is indicating a low water scarce area (EEA, 2016).

Box 4. Water Exploitation Index

The WEI+ is defined here as the total water net consumption divided by the freshwater resources of a region. WEI+ is calculate at monthly timesteps at regional level (water regions). The freshwater resources taken into account to calculate the WEI+ include locally generated runoff, inflowing surface water from upstream countries, lake and reservoir variable storage, and annual groundwater recharge.

The following classes are distinguished:

0.0 – 0.1	low water scarce region
0.1 – 0.2	moderate water scarce region
0.2 – 0.4	water scarce region
0.4 >>>	severely water scarce region

Within this study, the WEI+ is determined at monthly timescale and in subregions (typically subriver-basins within a single country). In this way, an averaging out effect is avoided. For a 30-year period, the 30*12=360 monthly values are then used, and for example averaged.

Figure 28 shows a computation of the WEI+ using observed meteorological data from 1990-2016 and as much as possible reported water demands. This value should correspond with values estimated by EEA (https://www.eea.europa.eu/data-and-maps/indicators/use-of-freshwater-resources-2/assessment-3).

Figure 29 shows a computation of the WEI+ using the 11 Euro-Cordex climate models for the baseline 1981-2010 period. The fact that these pictures are almost identical confirms that at least for the WEI, the climate simulations have no model-bias.

Figure 30 shows the WEI+ in a 2degree warmer climate, and figure 31 shows the difference of the WEI+ in a 2degree warmer climate as compared to current climate 1981-2010. These figures show that the areas of water scarcity under a 2 degree warmer climate stay more or less the same as at present, but the water scarcity intensifies in magnitude and duration (# months).

Figure 32 shows the WEI+ in an extreme RCP8.5 2070-2099 climate, and figure 33 shows the difference of the WEI+ in that extreme climate as compared to current climate 1981-2010. These figures show that water scarcity then also affects new areas in central Europe. Furthermore it is clear that in the Mediterranean there are many areas with a WEI+ close to 1.0, meaning that all possible water is being used, and likely also a substantial amount of fossile groundwater.

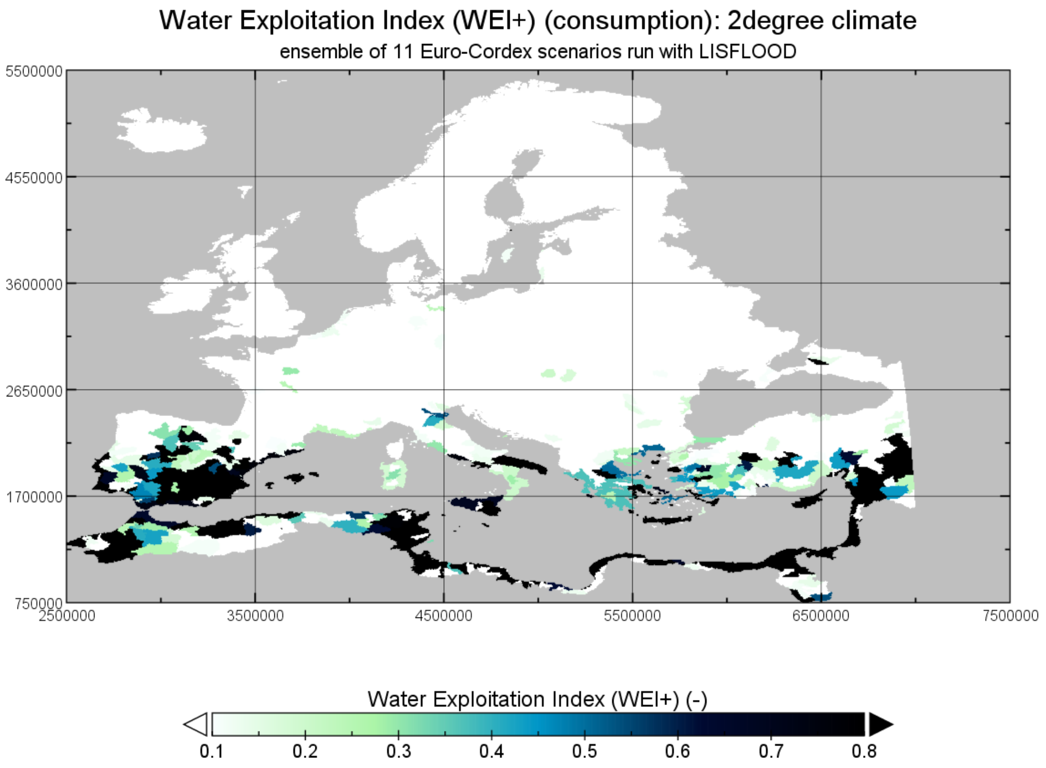

Figure 30 The Water Exploitation Index (WEI+) for Europe under a 2 degree changed (1981-2010) (ensemble of the 11 Cordex models).

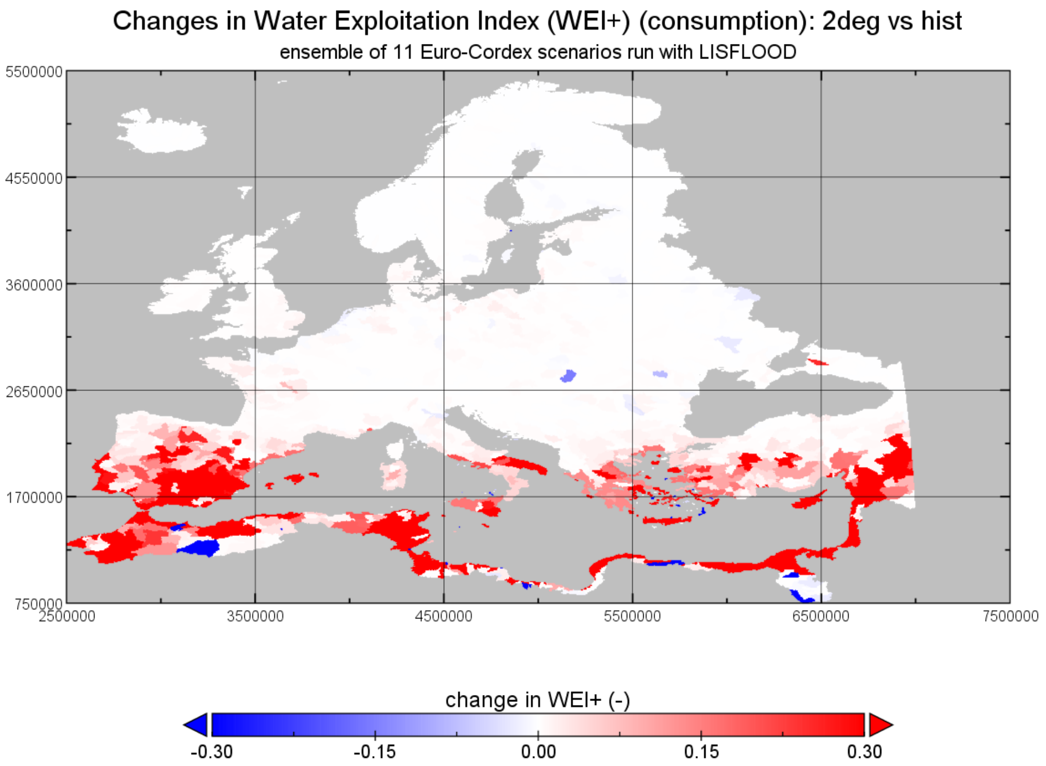

Figure 31 The difference of the Water Exploitation Index (WEI+) between the 2 degree changed climate compared to the control climate (1981-2010) (ensemble of the 11 Cordex models).

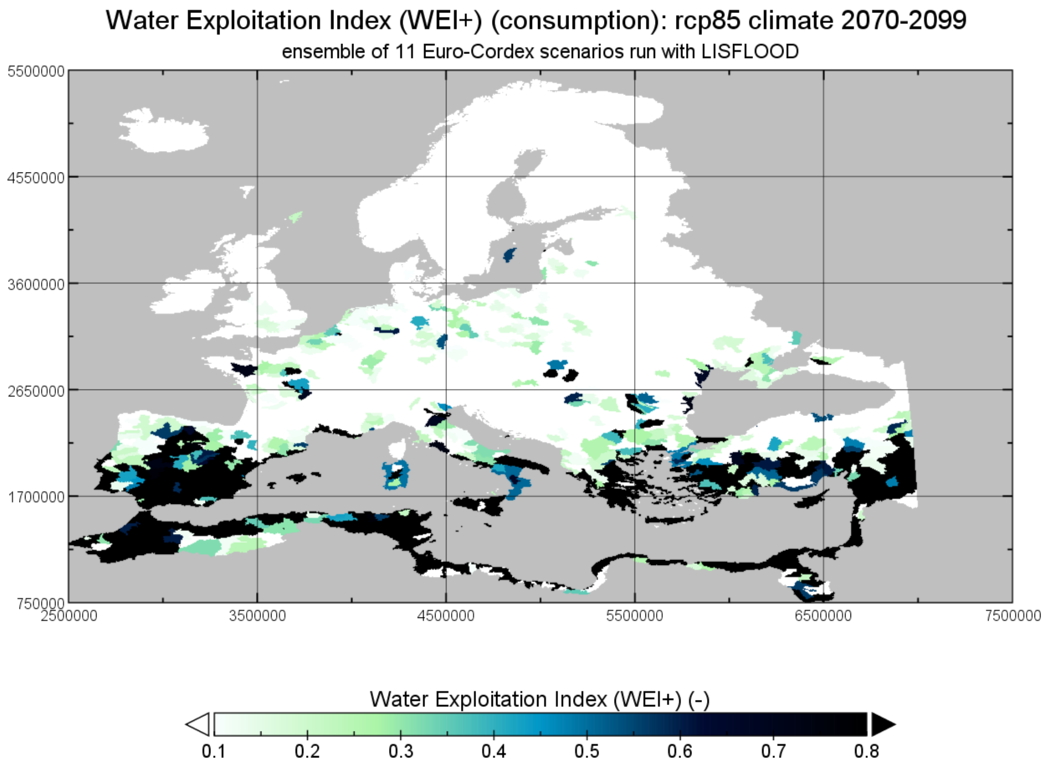

Figure 32 The Water Exploitation Index (WEI+) for Europe under an RCP8.5 2070-2099 climate (ensemble of the 11 Cordex models).

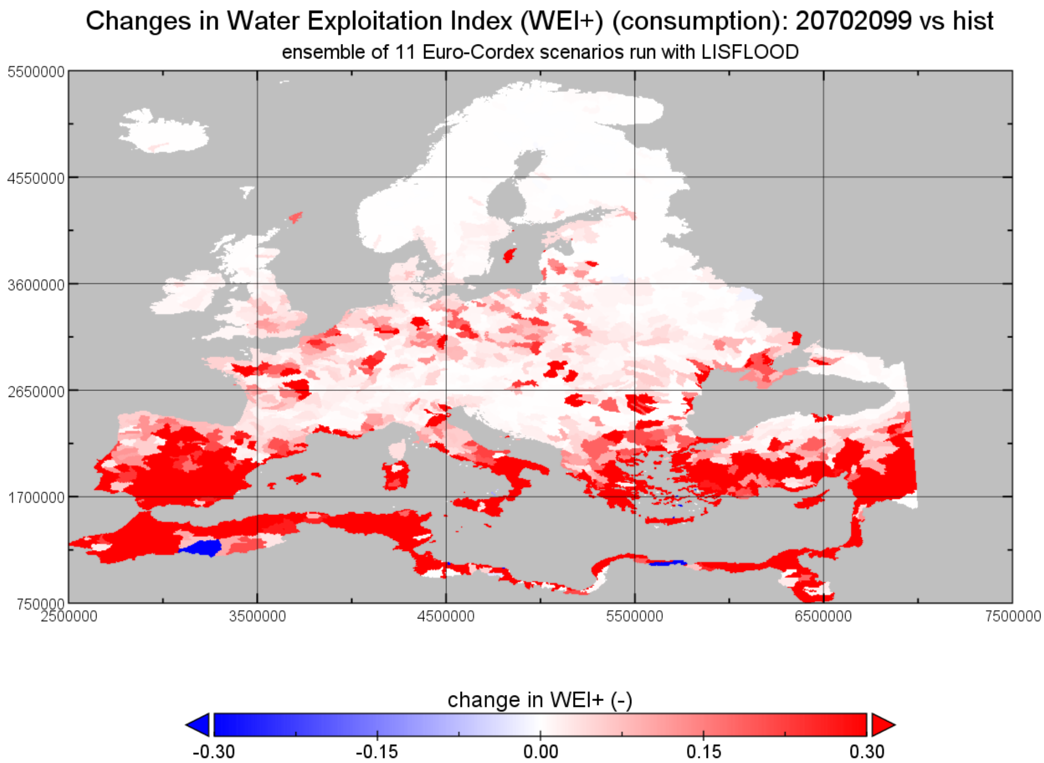

Figure 33 The difference of the Water Exploitation Index (WEI+) between the RCP8.5 2070-2099 climate compared to the control climate (1981-2010) (ensemble of the 11 Cordex models).

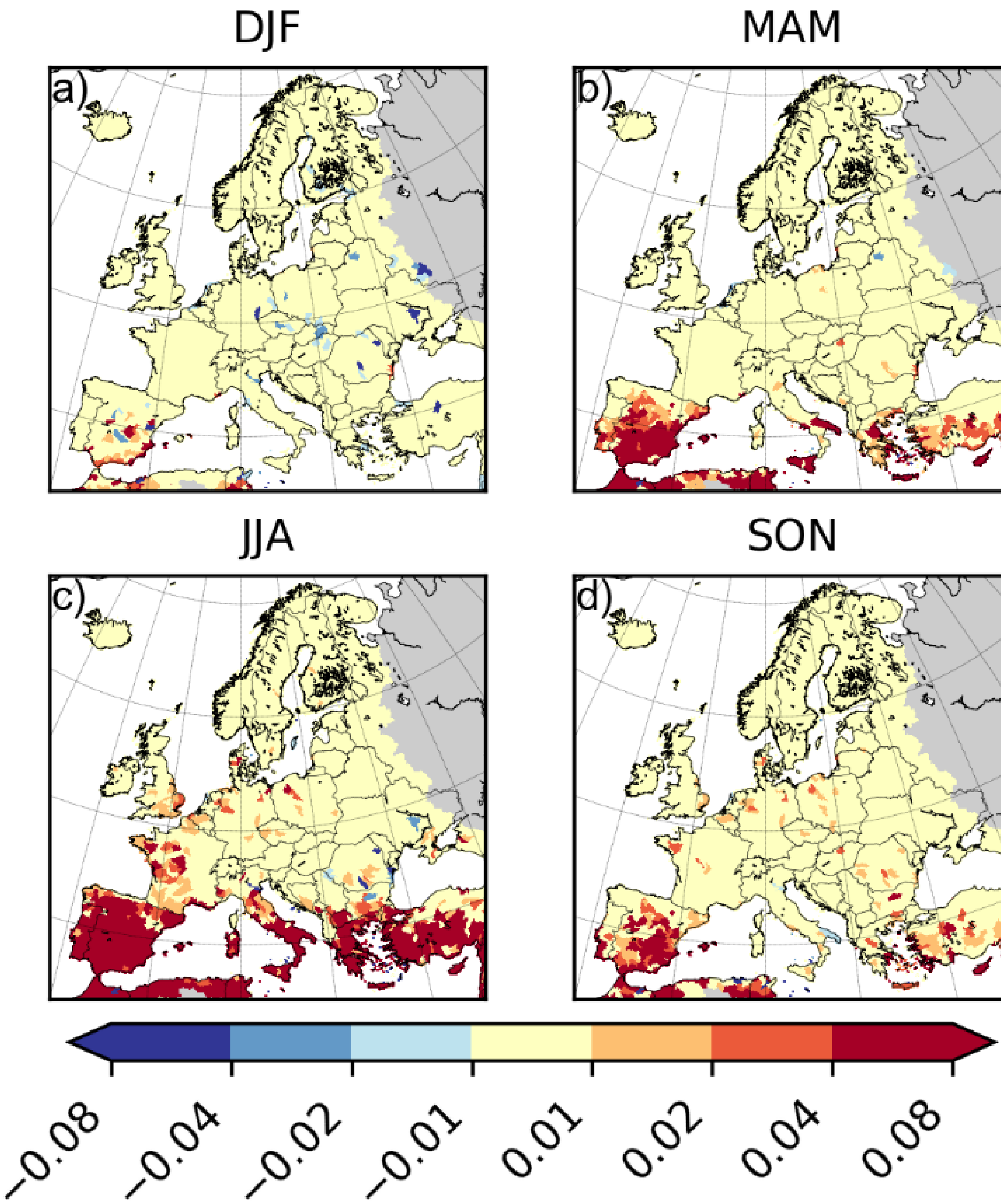

Figure 34 Seasonal changes of the Water Exploitation Index (WEI+) between the 2 degree changed climate compared to the control climate (1981-2010) (ensemble of the 11 Cordex models).

Figures 34 and 35 show seasonal changes of the WEI+, with most extreme changes in summer in the Mediterranean, but also increasing water scarcity issues in springtime and autumn.

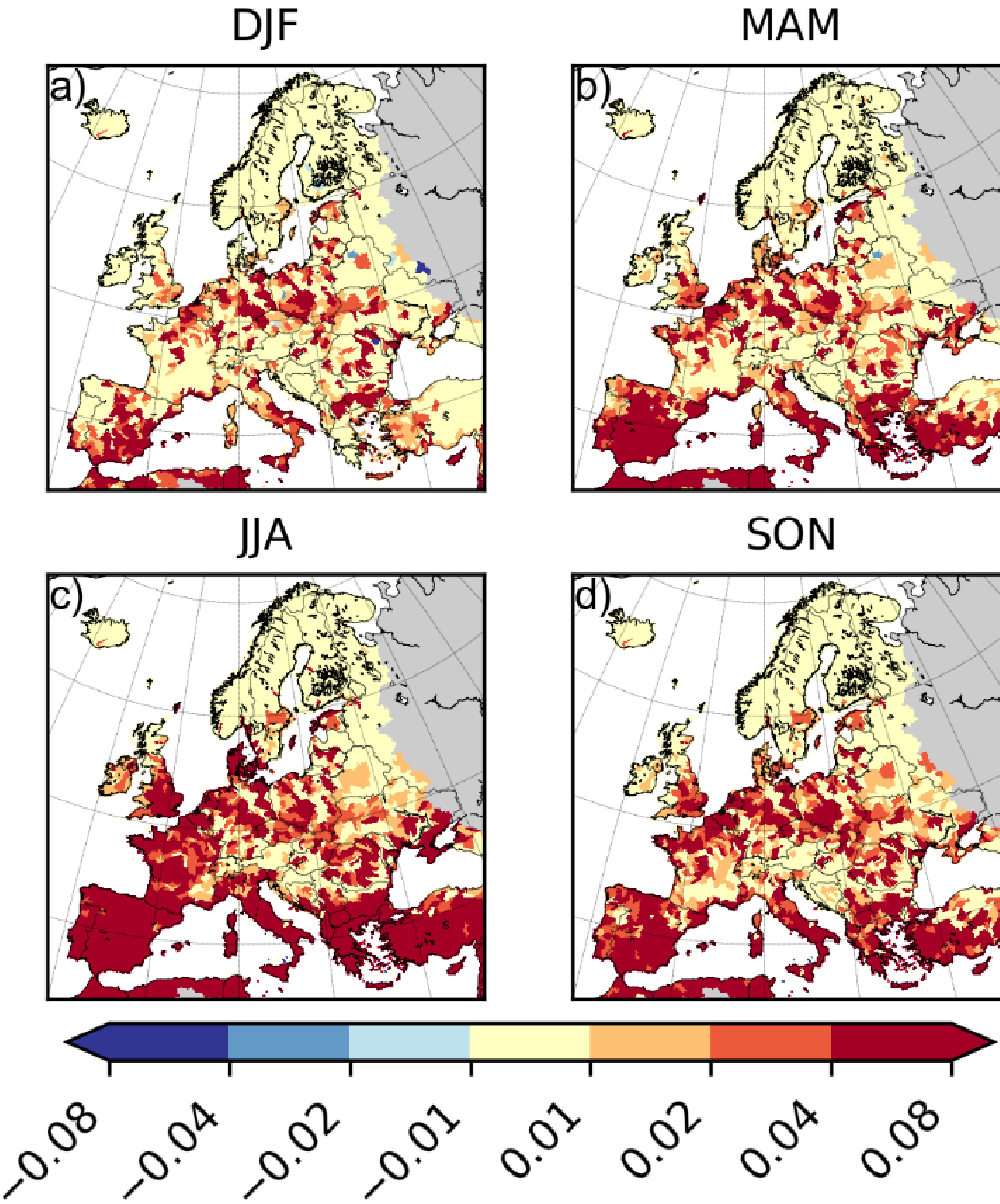

Figure 35 Seasonal changes of the Water Exploitation Index (WEI+) between the RCP8.5 2070-2099 climate compared to the control climate (1981-2010) (ensemble of the 11 Cordex models).

Figure 35 shows also new intense water scarce areas in the UK, France, Belgium, The Netherlands, Germany, Denmark and Poland, especially for the summer months, but also in autumn.

7.5 Impact of climate change on population affected by water scarcity

To put the water scarcity (WS) into a societal perspective we estimate how many people will be living in areas with a WEI+ larger than 0.20 for at least 1 month per year. The robustness of these estimates are dependent on the agreement between the climate projections. In Figure 36, the number of climate models projecting a WEI+ > 0.2 for at least 1 month/year is presented.

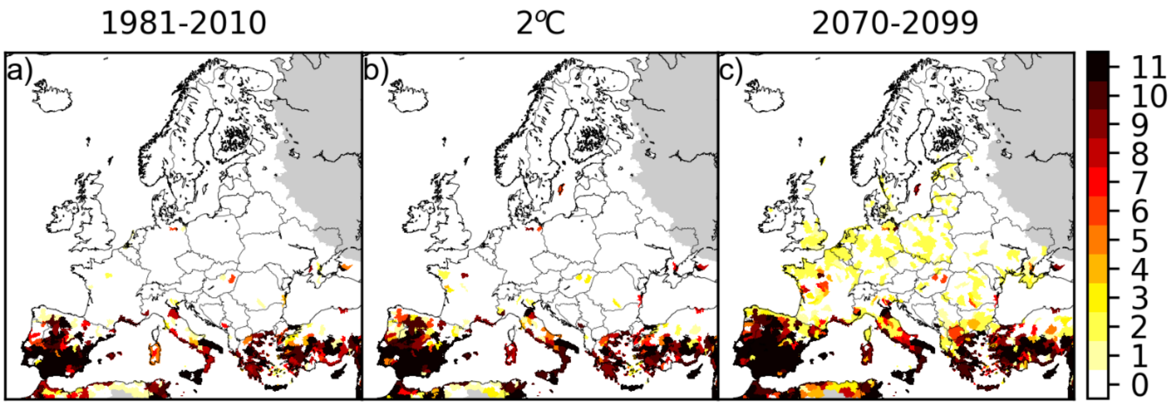

Figure 36 The number of climate models projecting a WEI+ > 0.2 for at least 1 month/year for a) the baseline 1981-2010, b) 2°C and c) 2070-2099 warming periods. The higher the number, the more likely the projected trend.

In the 1981-2010 control climate period the most robust signals are projected for the Mediterranean regions where up to 11 climate models project water scarcity (WS) (figure 36a). For the 2°C warming period the WS regions are almost similar compared to the 1981-2010 baseline period, but the robustness of the WS signal is increased (figure 36b). Towards the end of century (2070-2099) the WS regions are increasing, but mostly only projected by just 1 or 2 climate models (figure 36c).

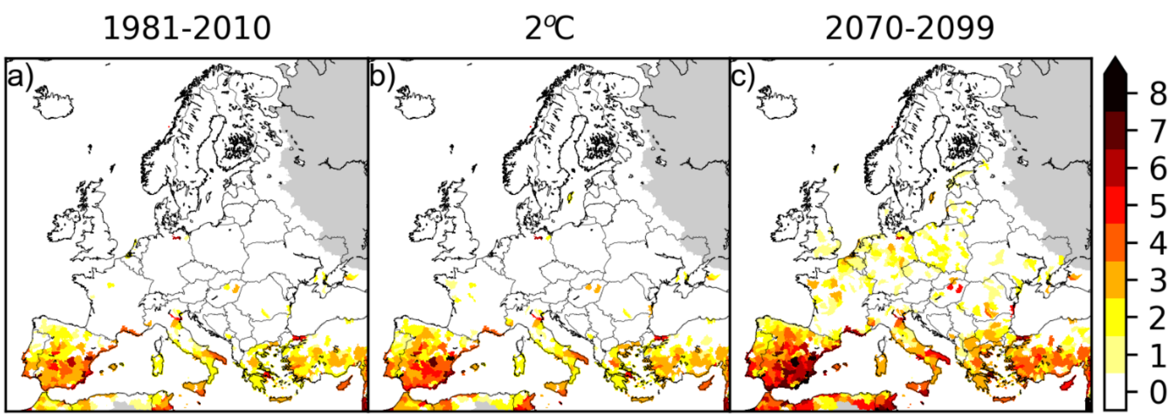

Figure 37 The number of months in a year with a WEI+ > 0.2 for at least 1 climate model for a) the baseline 1981-2010, b) 2°C and c) 2070-2099 warming periods.

The WS intensity in terms of number of months per year with a WEI+ > 0.2 is presented in figure 37. For the 1981-2010 period, WS is projected between 0-7 months/year in Spain and up to 5 months in the rest of the Mediterranean regions (Fig. 37a). These numbers are increasing for the 2°C warming period (Fig. 37b) and even more towards the end of century (Fig. 37c).

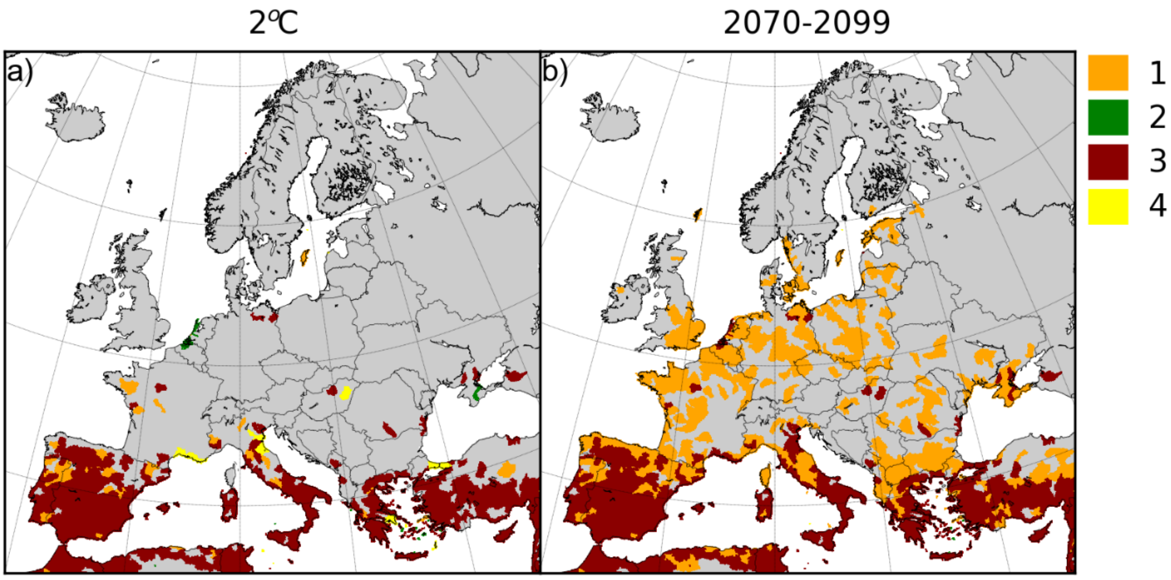

Figure 38 Regions where people are affected by WS categorized in 4 categories for the a) 2°C and b) 2070-2099 warming periods in relation to the baseline period (1981-2010):
Group 1 (orange): the number of people living in regions without WS but that become WS in future.
Group 2 (green): the number of people living in regions already WS but that become not WS.
Group 3 (dark red): the number of people living in regions which are already WS and become more WS (increase in months).
Group 4 (yellow): the number of people living in regions which are already WS and become less WS (decrease in months) but remain WS.

While estimating the number of people affected by WS, four groups of people are identified using the definitions of Gosling & Arnell (2016) and presented in figure 38:

1. The number of people living in regions without WS but that become WS in future (presented as orange in Fig 38)
2. The number of people living in regions already WS but that become not WS (presented as green in Fig 38)
3. The number of people living in regions which are already WS and become more WS (increase in months - presented as dark red in Fig 38)
4. The number of people living in regions which are already WS and become less WS (decrease in months) but remain WS (presented as yellow in Fig 38)

In the 2°C warming period, the regions with water scarcity are almost identical as during the control climate period 1981-2010 (figures 36a and 36b). Therefore, during the 2°C warming period the number of people affected by WS is almost equal compared to the current climate. However, figure 38a and figure 37b compared to figure 37a show that the people which are already affected by WS in the current climate are exposed to a longer period of WS within each year.

For the extreme warming scenario - end of century RCP8.5 - new WS regions are projected, as shown in figure 38b and figure 37c compared to figure 37b. Therefore, it is projected that more people will be exposed to WS in the extreme warming scenario.

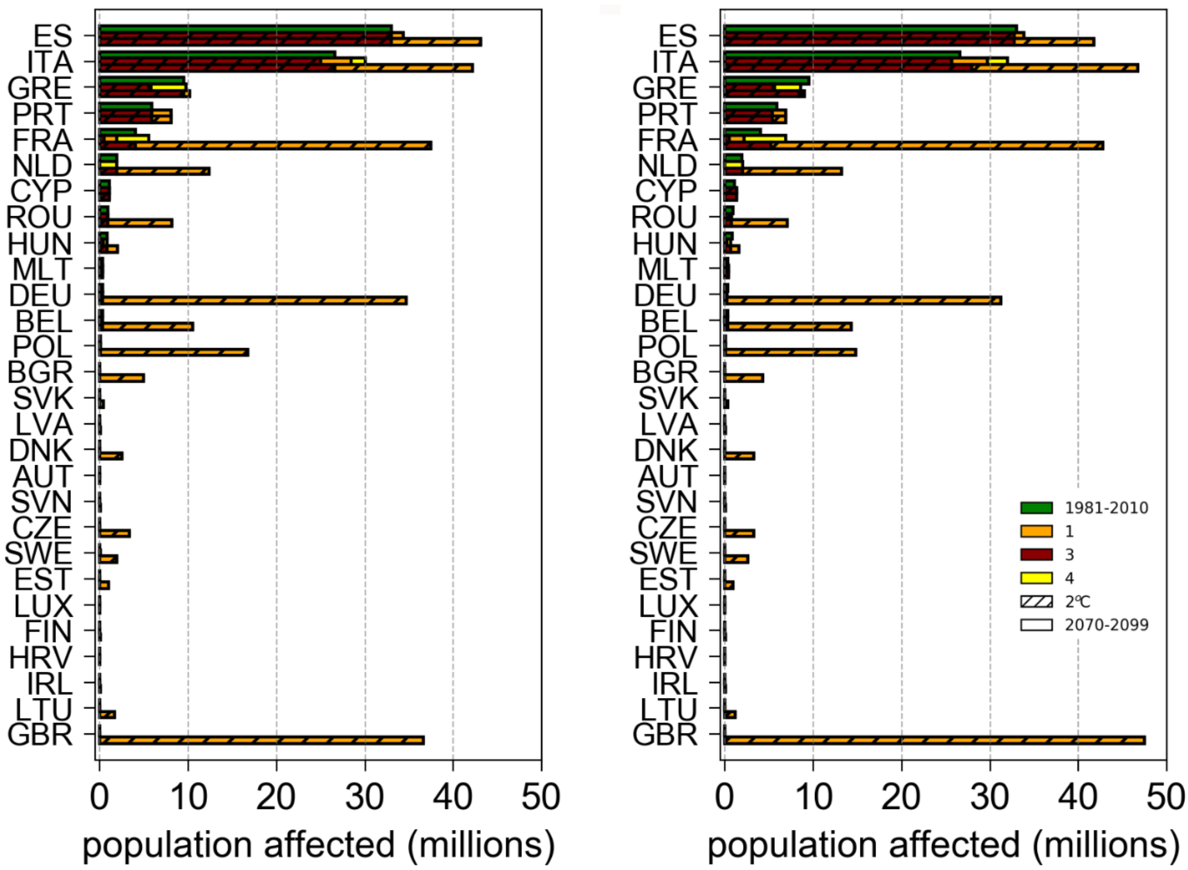

Figure 39 The number of people affected by WS (WEI+ > 0.2) for at least 1 month/year and for at least 1 climate model due to a) climate change, b) climate change and population change. Values are shown for the baseline 1981-2010, the 2°C warming scenario, and the extreme RCP8.5 2070-2099 scenario.

In figure 39 the number of people affected by WS is presented at country scale for the EU28 for the categories 1, 3 and 4 as the sum of these categories present the number of people living in WS areas. As all the climate scenarios are equally plausible, we assumed the number of people affected when at least 1 out of 11 climate scenarios projected WS (figure 36). Therefore, the results in figure 39 should be interpreted as the maximum potential number of people affected by WS.

In the current climate, most people affected by WS live in southern Europe. In Spain we estimate that 33 million persons are affected, and in Italy 27 million people. We estimate that in total 85 million people in Europe are affected by WS under current climate.

As in our simulations both population numbers are changing from 2010 to 2050, and the climate and thus water scarcity is changing, we evaluate the effect of climate only (figure 39a) and the combined effect of climate and population change (figure 39b). In some countries a population decrease is projected that influences the results here. In France for example there is by 2050 also a population growth of ~6 million people projected, whereas in Spain, Portugal, Poland and Germany, a population decrease of several millions is projected.

Under the 2°C warming period it is projected that the number of affected people increases slightly from 85 to 94 million persons without taking the population change into account, mainly in the Mediterranean countries. However, the duration and intensity of the water scarcity is increasing. In Spain and Portugal the numbers decrease due to population decrease, while in Italy and France the population growth increases the number of people affected by WS resulting in an equal number of people affected: 94 million persons. In the 2°C warming scenario, the people living in the rest of the European countries are not much more affected by WS compared to baseline period 1981-2010, or at least those areas do not reach our set threshold of at least 1 month per year water scarcity.

For the 2070-2099 warming period, the water scarce areas in Europe are expanding northwards and therefore we project an increase of people living in WS areas. For the EU28 part of the Mediterranean (Portugal, Spain, Italy and Greece), we project that the number of persons affected by water scarcity increases from 85 million under current climate to 104 million under changed climate and population. This number includes a further increase of population in (northern) Italy of 0.8 million persons. This projected climate and scarcity change is robust, as several models confirm this trend.

However, as the water scarcity areas expand also in a northern direction, also other countries then only the Mediterranean region are projected to be affected by water scarcity under the extreme warming scenario, such as France (37 million persons), Germany (35 million persons) and Great Britain (37 million persons). Note that the results for these countries are not very robust as they are sometimes based on only a single climate scenario from the eleven in total.

To summarize, under an extreme warming scenario, the number of persons affected by water scarcity in EU28 countries could increase from the current 85 million to 104 million (Mediterranean - robust) or potentially 295 million (EU28 - less robust). Under the 2°C warming period it is projected that the number of affected people increases slightly from 85 to 94 million persons, mainly in the Mediterranean countries.

7.6 Impact of climate change on soil moisture stress

The Root Water Stress indicator (RWS) as used in the LISFLOOD model is an indicator that shows the reduction of crop and/or vegetation transpiration due to limited water availability. The vegetation gets water stressed, and this might influence vegetation and crop growth and result in yield losses, or even crop failure.

When the soil is wet, the water is relatively free to move and is easily taken up by the plant roots. In dry soils, the water is strongly bound by capillary and absorptive forces to the soil matrix, and is less easily extracted by the crop. Within the LISFLOOD model, an RWS value of 0 means that the soil is nearly completely dry and vegetation is at wilting point. An RWS value of 1 means no water stress. This can still be a dry soil at around pF 3 or so, but the vegetation has still sufficient capacity to abstract water from the soil.

In figure 40 the annual RWS changes are presented comparing the 2-degree changed climate with the control climate 1981-2010. Figure 41 shows the same values but then for the summer period (JJA) which is obviously the most important influence on the annual values of RWS. The same spatial patterns are visible, but more intense than in figure 40.

Figures 40 and 41 show a tendency of increased soil moisture stress in large parts of Europe, including France and UK. Areas which are currently already often stressed in the Mediterranean will become even more stressed under the 2°C warming scenario.

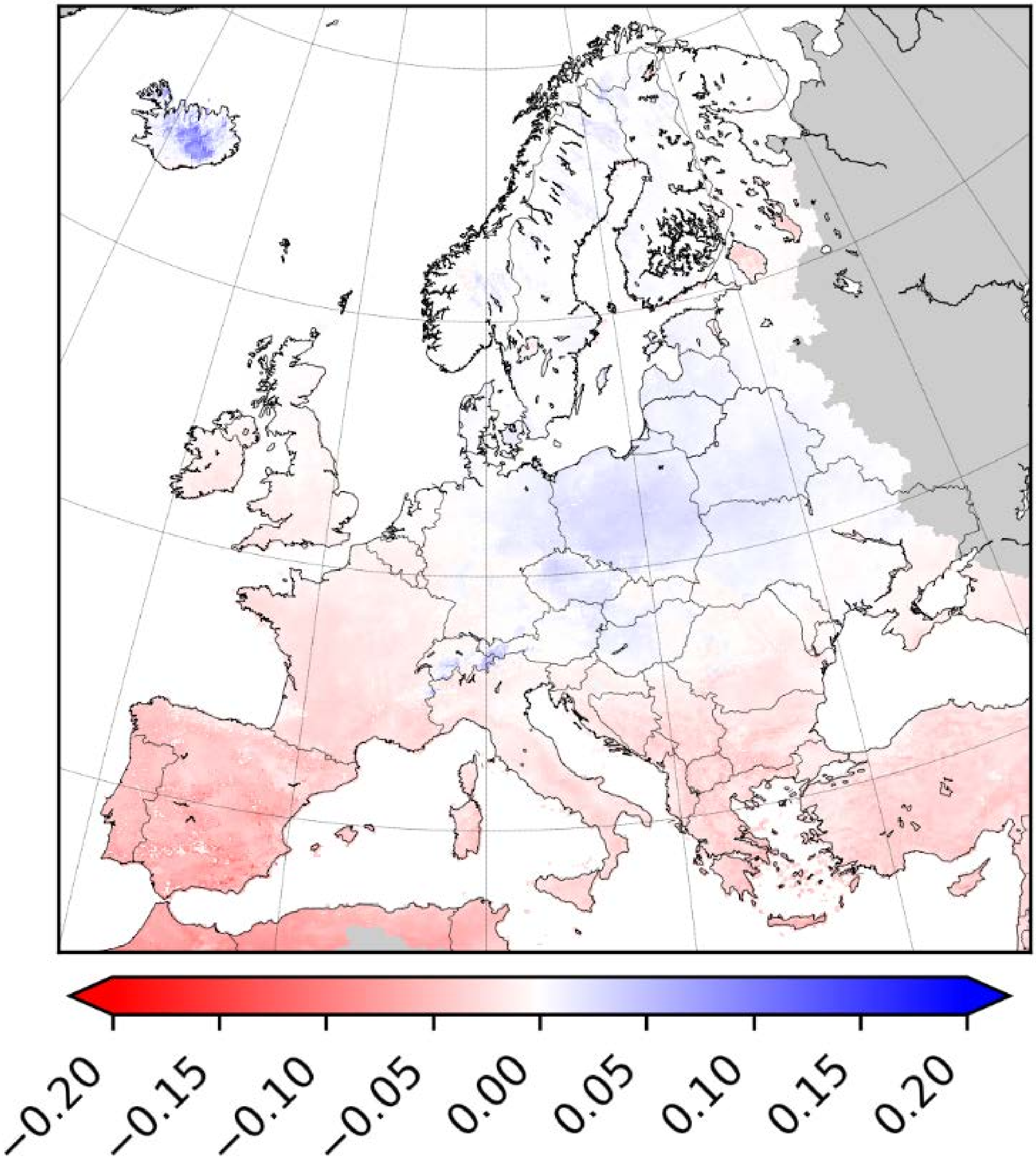

Figure 40 Projected annual changes in soil moisture stress under a 2 degree changed climate. Ensemble of 11 Euro-Cordex models run with the LISFLOOD model. Note: an average RWS value of 1.0 would mean that there is never soil water stress. A value of 0.0 would mean there is extreme water stress every single day. If only one month per year would be complete water stressed, and the others not at all, the RWS would be 0.915. Changes of 0.10 are thus substantial already. Negative values indicate drier than now conditions, positive values mean wetter than current climate.

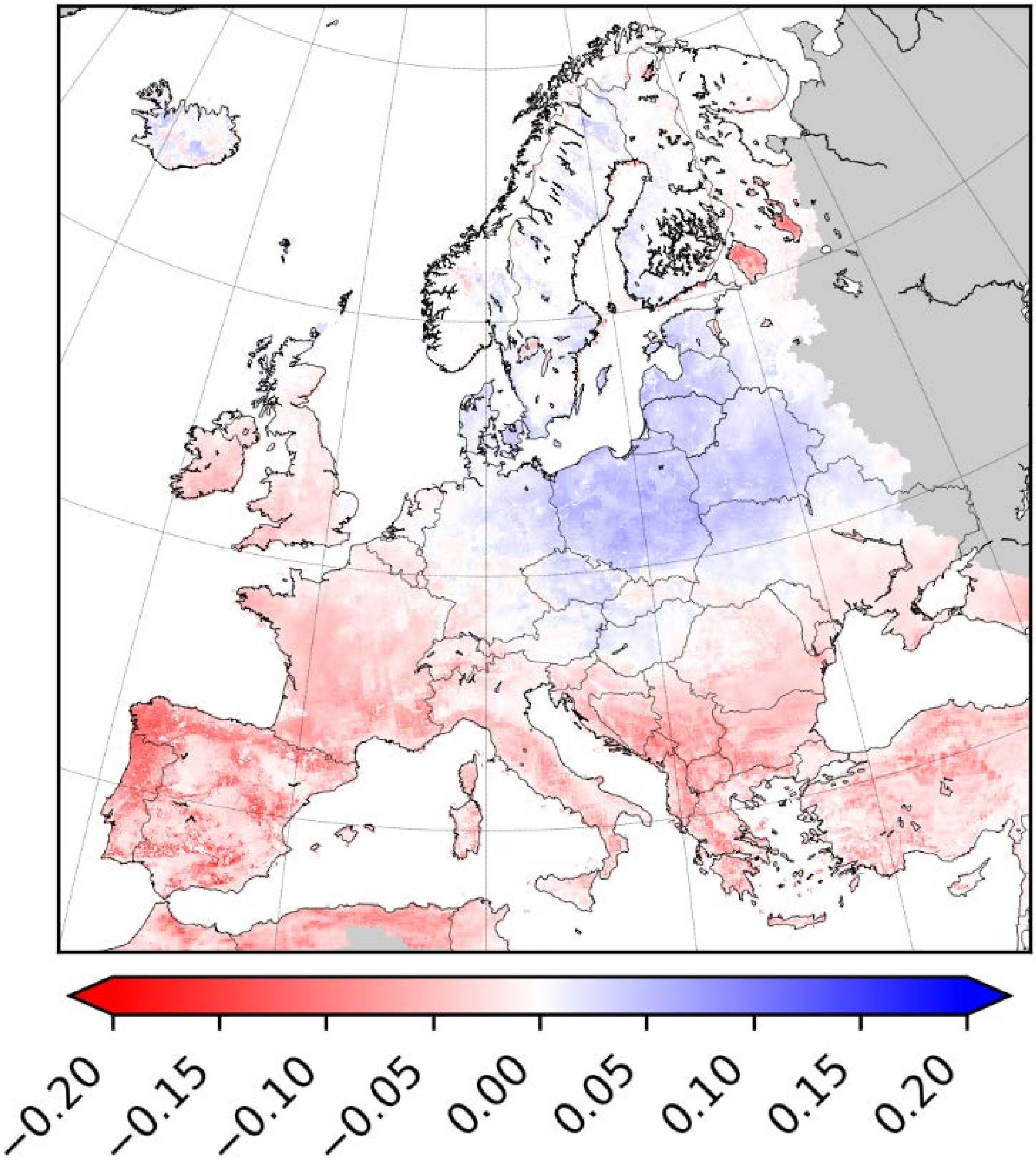

Figure 41 Projected summer month (JJA) changes in soil moisture stress under a 2 degree changed climate. Negative values indicate drier than now conditions, positive values mean wetter than current climate. Ensemble of 11 Euro-Cordex models run with the LISFLOOD model.

7.7 Impact on possible irrigation and other water shortages

The LISFLOOD model also simulates cases where there is not sufficient water available to meet the demands of the various sectors: irrigation, cooling, manufacturing industry, livestock, public water, environment. When during individual days a local demand for water abstraction is larger than the availability, the model does not allow for the part of abstraction availability and flags this amount as shortage. This shortage is accumulated to get an overview.

Water can be abstracted from groundwater, surface water, or by using non-conventional sources (e.g. desalination). LISFLOOD uses country-scale coefficients from FAO-Aquastat which indicate the percentage of irrigation demands that are met by groundwater, surface water, or non-conventional sources; So, a fixed percentage of water abstraction comes from groundwater.

In this study, groundwater abstraction is not restricted by availability, i.e. we assume infinite availability. Restrictions of maximum allowed groundwater depth and consequent pumping costs, or the usage of fossile groundwater beyond annual recharge are not yet implemented; in ongoing work, we are executing some scenarios with this.

For surface water abstractions, we are not yet applying water allocation rules, but we do implement the following restrictions:

- Abstraction from lakes and reservoirs: LISFLOOD is set here to allow for 25% of surface water abstraction from nearby lakes and reservoirs, but not beyond the annual renewable inflow of those lakes and reservoirs. Basically this is done because of a lack of information on actual abstractions from lakes and reservoirs. We collaborate with the EEA water account team aiming to improve this, but there we rely on MS reporting.
- Abstractions from rivers: When abstractions from groundwater and lakes and reservoirs are done, the remaining water will be withdrawn from rivers. However, no abstraction below a user-defined ecological flow threshold is allowed.
- In the study here, a mild ecological flow threshold of 1.0 m3/s everywhere was applied. Below that threshold, abstraction is not allowed, and the model flags this amount of water as water shortage. We could have chosen also a more stringent eflow threshold of Q5 or Q10, which would lead to much more water shortage. Also here in ongoing work we use other e-flow thresholds, such as the 10^{th} percentile (Q10) discharge as threshold. Scientific and political consensus on e-flow however does not exist yet. If consensus is available, we will implement it in LISFOOD.

Figure 42 shows the projected increase of 'actual' water shortages in m3 for European countries, in a 2 degree climate as compared to current climate. Considerable additional shortages as compared to present are projected for Spain, Hungary, Italy, Germany, Portugal and Greece. Other countries with increased projected shortages include Lithuania, France, Bulgaria, Poland and Romania.

The projected shortage for Spain – related to surface water abstraction only – is 1400 Mm3/year, compared to e.g. the reported abstractions of 21700 Mm3/year (Wriedt et al., 2008).

In many countries in Europe the allocation rules are such, that abstractions for irrigation are restricted first in many cases. Also, intake of cooling water, either because of limited amounts but often also due to high water temperatures, can be restricted during periods of warm weather and/or low flow.

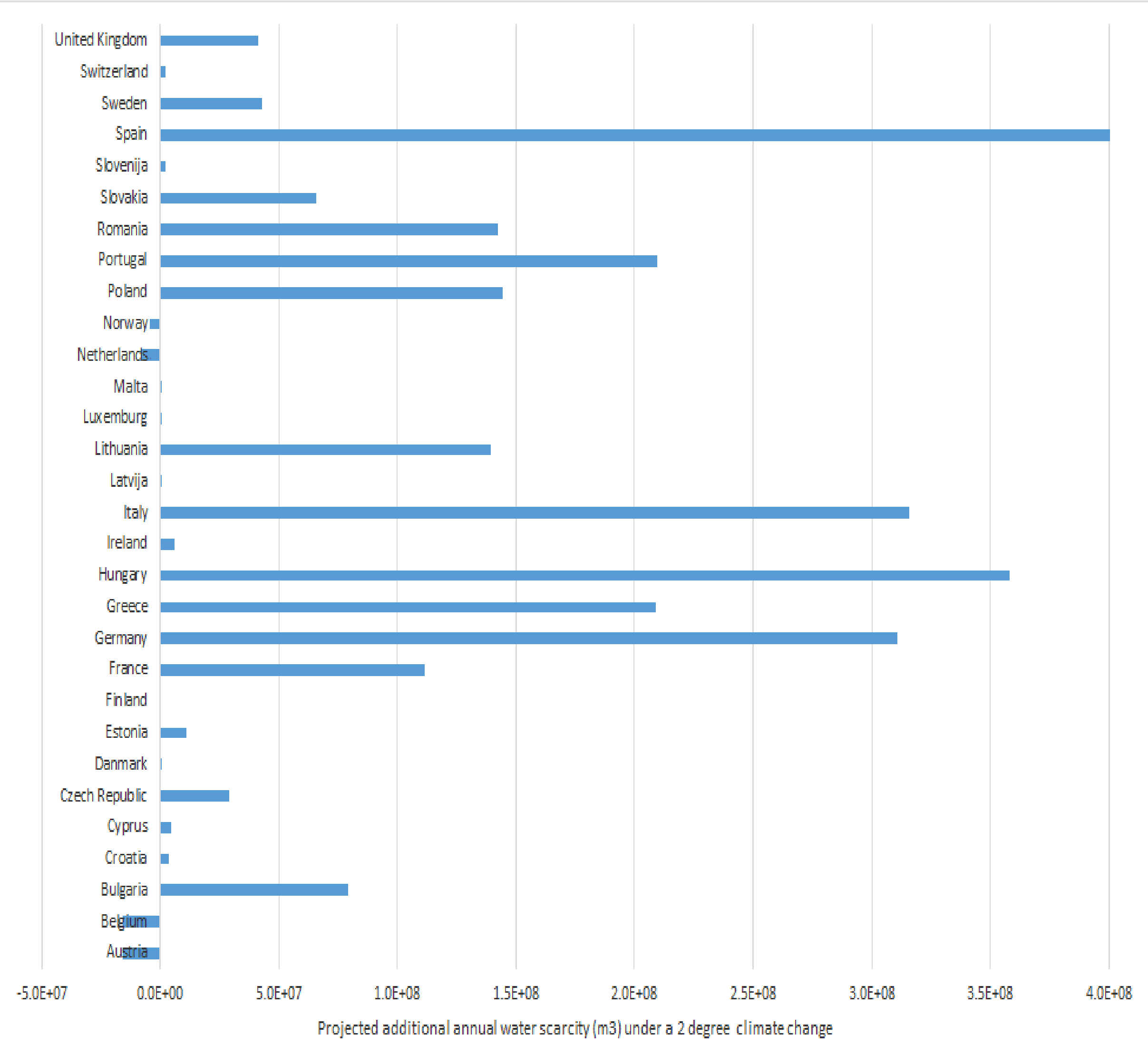

Figure 42 Projected additional annual water scarcity under a 2 degree climate, as compared to current climate. This refers to shortage of water for abstractions, and it does not consider rainfed shortages. Note: the projected value for Spain is 1.4E+09 m3/year, and goes off scale.

7.8 Impact of climate change on groundwater resources

The LISFLOOD model estimates of groundwater recharge change under a 2 degree climate (figure 43) show a decreasing trend for the Mediterranean and Northern Africa.

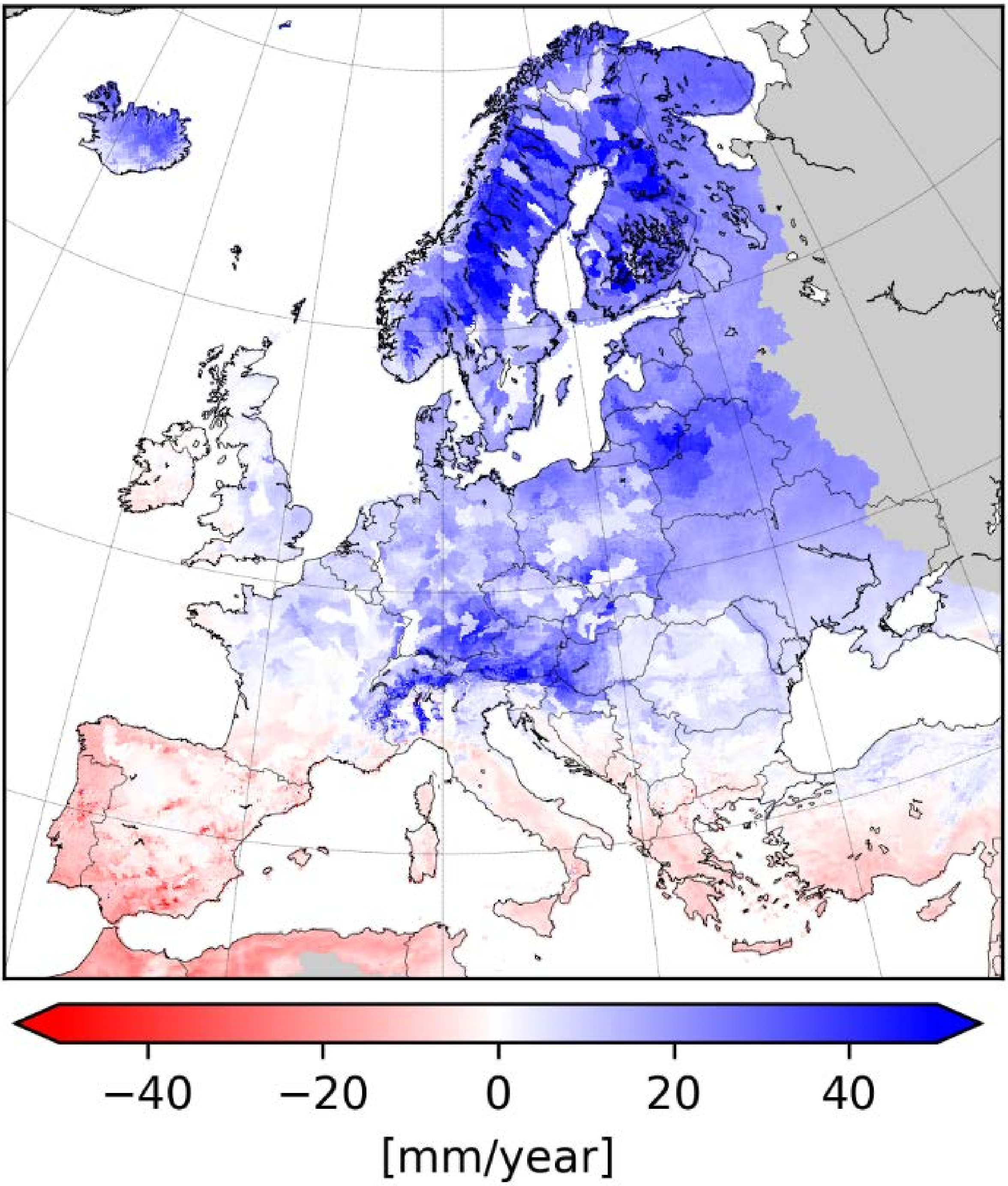

Figure 43 Impact of 2 degree climate change on groundwater recharge, as compared to the control climate 1981-2010. Ensemble of 11 Euro-Cordex models run with the LISFLOOD model.

The Alps and north of the Alps show an increase in groundwater recharge. Ireland and large parts of France show tendencies of slight decreases as well.

In figure 44 we accumulated the changes in annual groundwater recharge under the 2 degree warming scenario. Spain (-3272 Mm3/year), Portugal (-1080 Mm3/year), and Greece (-810E Mm3/year) are estimated to have significant reductions in groundwater recharge

The groundwater recharge reduction estimated for Spain - 3272 Mm3/year – is 15% of the reported annual amount of abstracted water for irrigation.

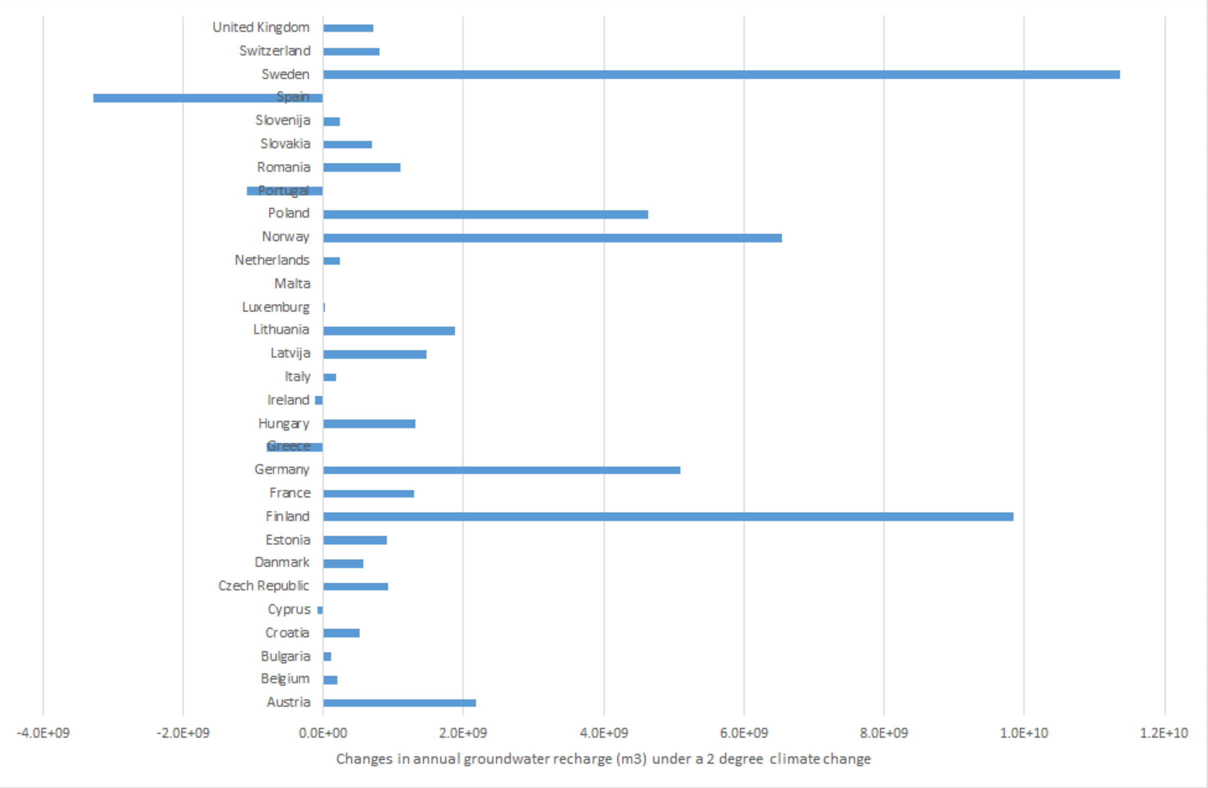

Figure 44 Changes in annual groundwater recharge under a 2 degree climate change.

7.9 Impact on water availability for hydropower

The energy sector needs freshwater as a source for hydropower and for cooling thermoelectric power plants. We examined the results of the water resources modelling here for both hydropower and cooling.

We examined 835 main hydropower locations in Europe on their water availability, specifically by their mean inflow into their reservoirs. We divided Europe into six regions. We made an East-West division near Berlin, North-Mid-South divisions were made at Hamburg and Milan:

- SW – SouthWest - Spain, Portugal, Southern France, Northern Italy
- MW – MidWest - France, Benelux, Germany
- NW – NorthWest - UK, Ireland, Norway
- NE – NorthEast - Sweden, Finland, Baltic States
- ME – MidEast - Poland, Czech Republic, Hungary, Austria
- SE – SouthEast - Greece, Southern Italy, Croatia, Serbia, Romania, Bulgaria

In line with the results on discharge reported earlier in this document, we project for the 2-degree climate change a slight (~4%) decreases of hydropower inflow for the SW region - consisting of Spain, Portugal, Southern France and Northern Italy – and the SE region (~2%)- consisting of the Balkans, Greece and Southern Italy. However, both decreases and increases are projected for those regions. For NE Europe, we project increases for hydropower locations with around 13%, potentially leading to local dam safety issues.

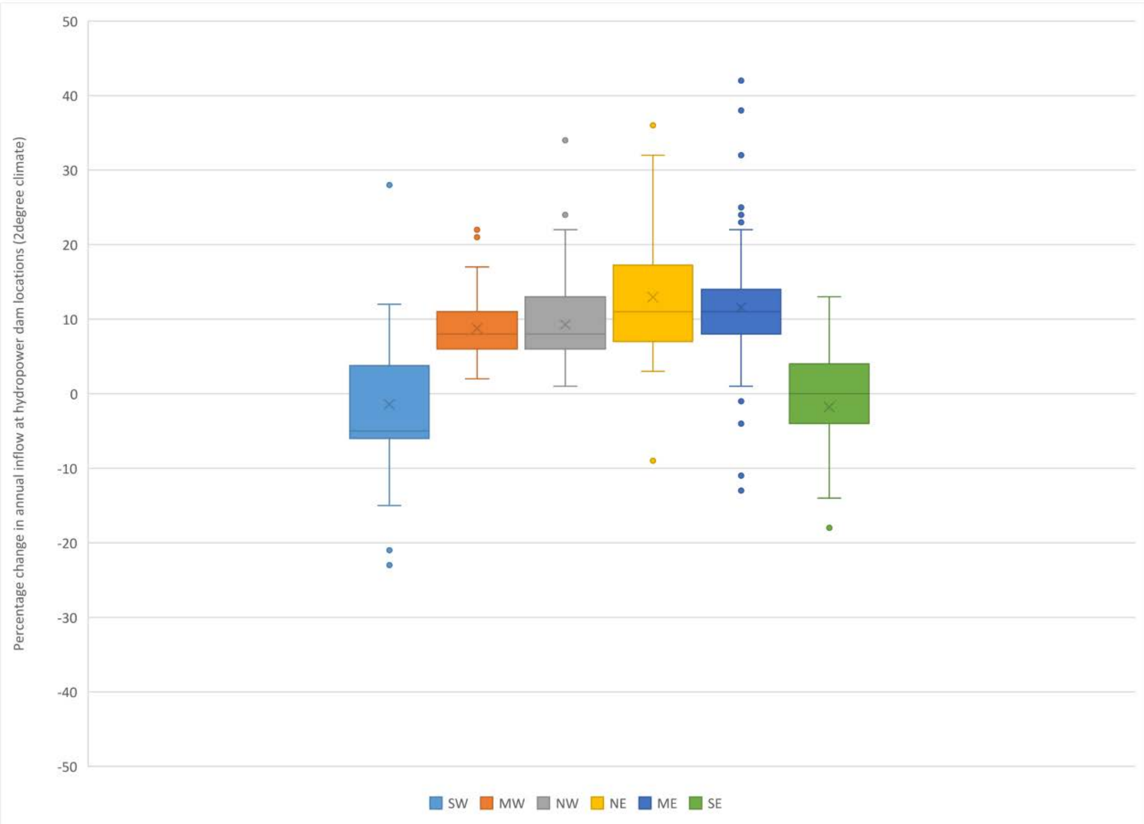

Figure 45 Changes of average annual inflow (Qavg) at hydropower stations in 6 European regions for the 2 degree climate change as compared to current climate 1981-2010: ensemble of 11 Euro-Cordex models run with the LISFLOOD model.

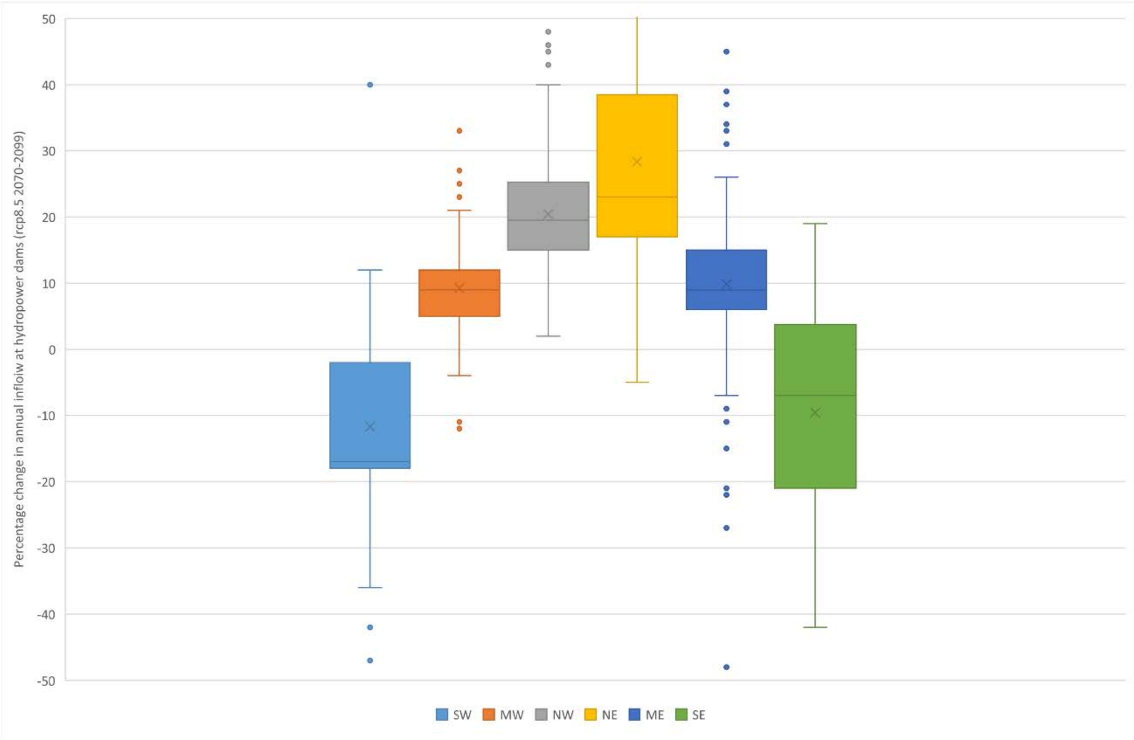

Figure 46 Changes of average annual inflow (Qavg) at hydropower stations in 6 European regions for the RCP8.5 2070-2099 climate change as compared to current climate 1981-2010: ensemble of 11 Euro-Cordex models run with the LISFLOOD model.

For the end of the century RCP8.5 climate, we do project a far more extreme picture, with 12% decreases in hydropower inflow in the SW region, and 10% decreases in the SE region. For NE Europe, we project increases for hydropower locations with around 28%, potentially leading to widespread dam safety issues.

7.10 Impact on water availability for cooling energy plants

Substantial volumes of water are used in the energy sector for cooling thermoelectric power plants. Already in the present climate it might happen that there is either not sufficient cooling water available during summer days, or that the temperature of the available surface water is too high to be used as cooling water.

Water temperature is not examined here, but we looked at water quantities at 433 cooling locations at thermoelectric plants.

Here, we investigate the future projection of the Q5 percentile streamflow as an indicator for sufficient fresh water for thermoelectric cooling, since especially during low flow periods there might be abstraction limitations to meet other constraints such as environmental flow and water temperatures.

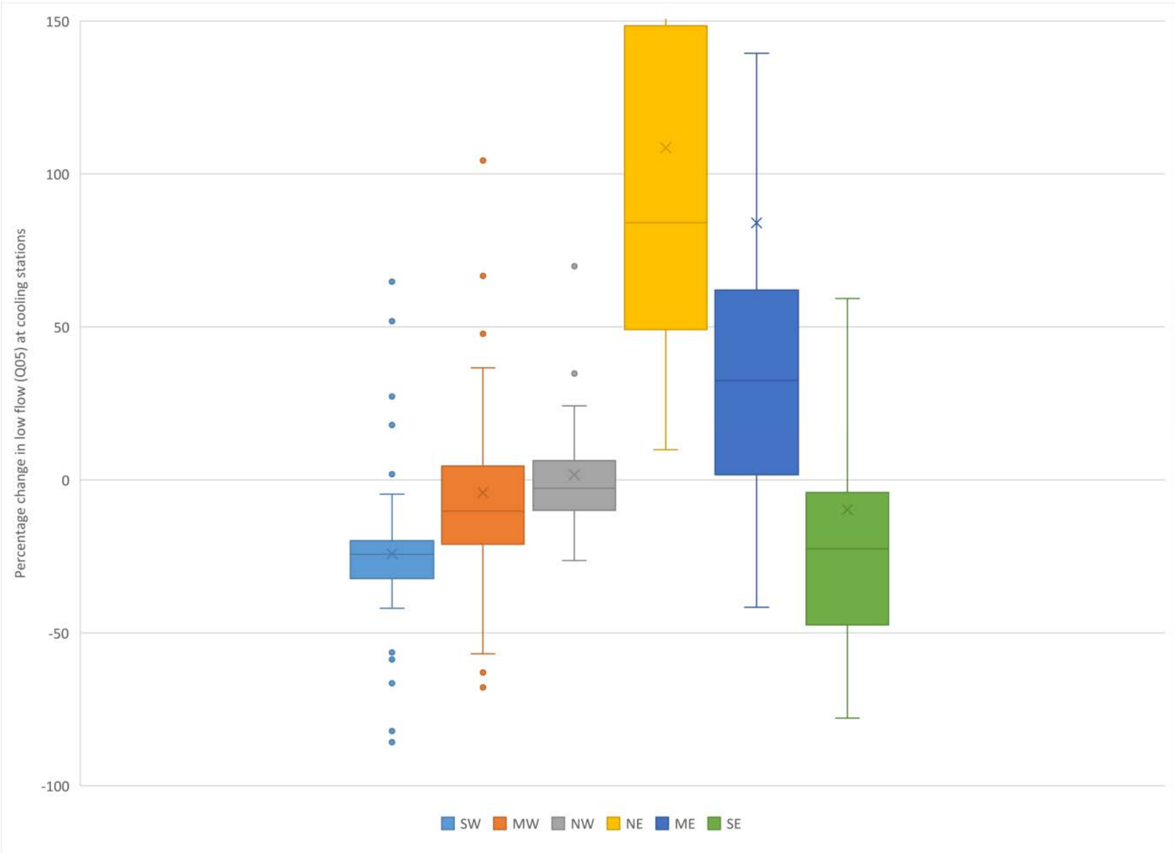

Figure 47 The projected change in low-flow (Q5) near thermo-electric power stations, for the RCP8.5 2070-2099 climate as compared to current climate. Ensemble of 11 Euro-Cordex models run with the LISFLOOD model.

Figure 47 shows projected significant decreases of low flows of around 25% in the SW region (Spain, Portugal, Southern France, parts of Italy) and also in the SE region (Greecse, Southern Italy, Balkan countries). For Scandinavian countries and Eastern European countries the low flow numbers are increasing.

Water temperature is currently not simulated in LISFLOOD but is under development within the next update.

7.11 Impact on water surplus and water scarcity in urban areas

Urban sealed areas are more susceptible to pluvial flooding compared to other natural surfaces due to little or no infiltration. Tunnels, underpasses, cellars of houses are all vulnerable to this type of flooding. Also, urban drainage systems – which aim to capture and discharge the surplus water - are often based on design flows under historic climates, which may not be valid anymore. During heavy rainfall intensities or prolonged rainfall, when the limits of both soil storage capacity and urban drainage systems are exceeded, water is ponding or running off in preferential flow paths on the ground surface depending on the topography. Due to climate change and land use change including urban expansion this is expected to occur more often in the future with high potential impacts.

Figure 48 shows the projected changed in annual local runoff under a 2 degree changed climate.

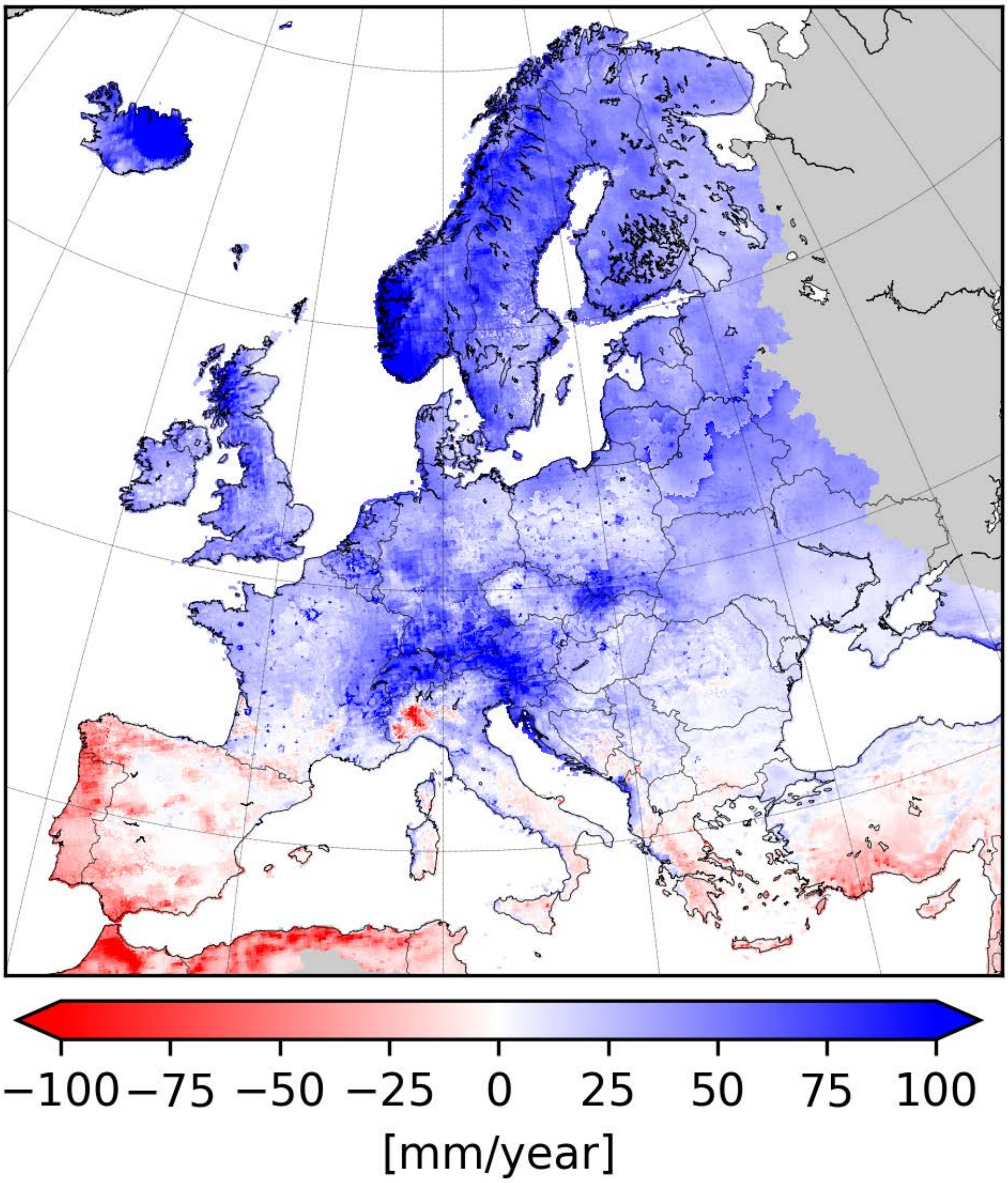

Figure 48 Change in local runoff under a 2 degree climate compared to control climate 1981-2010.

We further evaluated the changes in runoff for 672 Functional Urban Areas (FUA), or Larger Urban Zones (LUZ). The FUA's consist of a city and its commuting zone (Eurostat, 2004, Lavalle et al. 2015).

Figure 49 shows the change in annual urban runoff under a 2degree climate for a number of FUA's in Europe. Most likely the urban areas are projected to be more vulnerable for pluvial flooding in a future climate. This is also in agreement with the precipitation projections and the projections of extreme flood events. From the investigated cities, only Lisbon, Seville and Athens are projected to have decreased annual runoff.

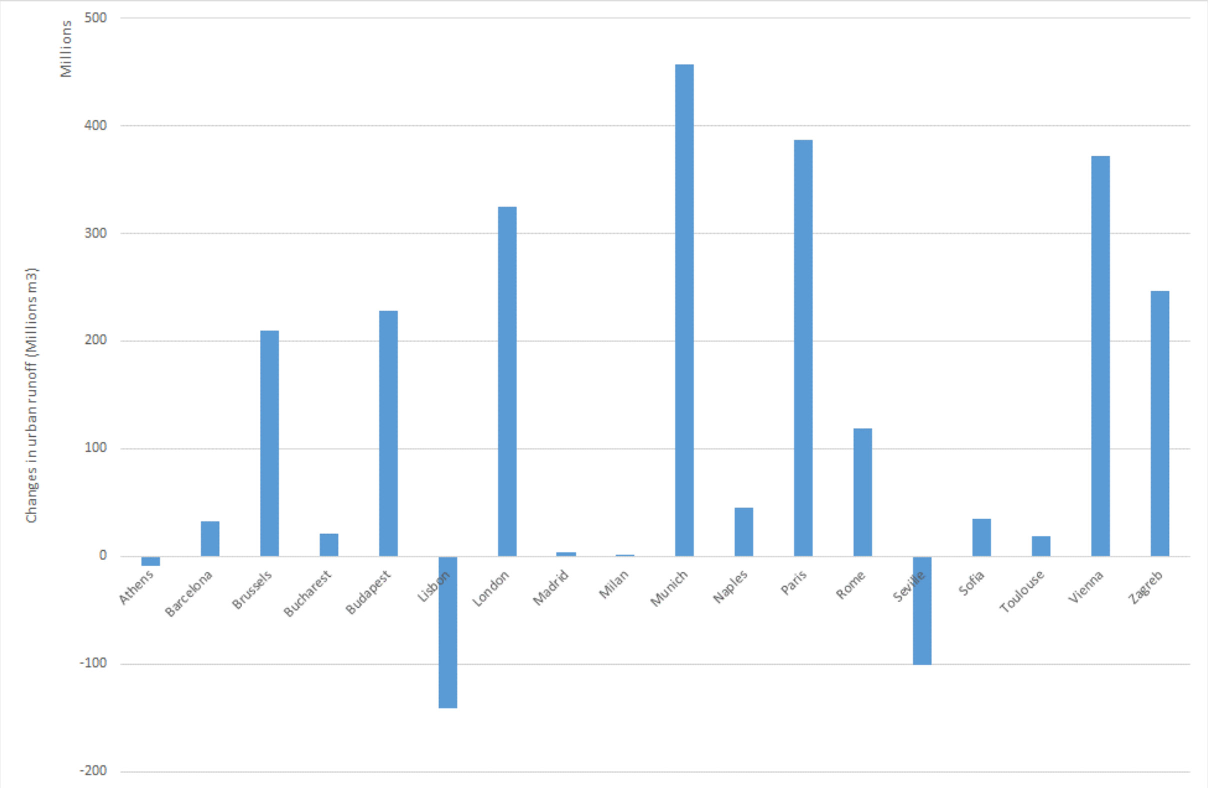

Figure 49 Change in annual urban runoff under a 2 degree climate compared to control climate 1981-2010 for a number of European functional urban areas (FUA's).

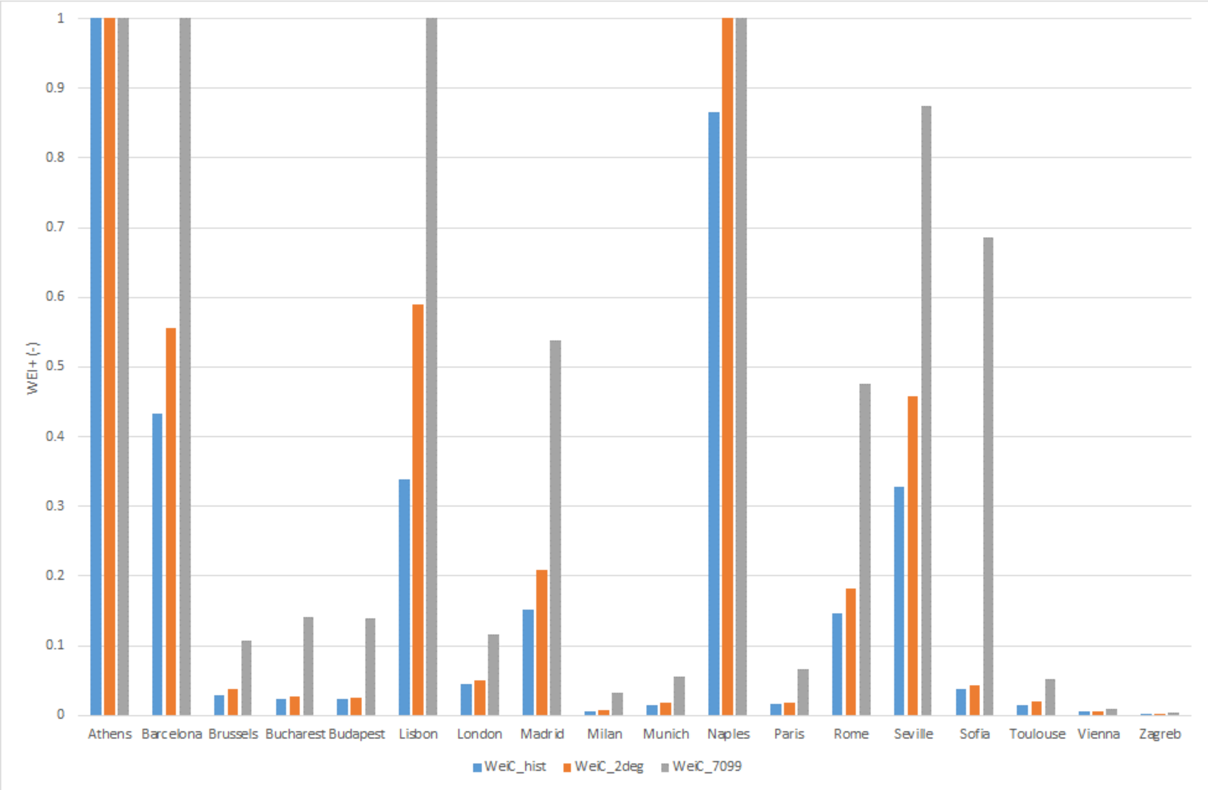

Figure 50 The average annual Water Exploitation Index (WEI+) for a number of European functional urban areas (FUA's), under current (control) climate 1981-2010 (hist), a 2 degree climate climate (2deg), and an RCP8.5 2070-2099 climate (7099).

Water scarcity on the other hand is another issue cities might encounter. Figure 50 shows the change of the Water Exploitation Index (WEI+) for a number of functional urban areas.

Athens, Barcelona, Lisbon, Madrid, Naples, Rome, Seville and Sofia are among the urban areas very much affected by water scarcity.

In general, it can be concluded from figure 50 that the 2 degree warming scenario causes an increase of WEI+ in some Southern European cities (Barcelona, Lisbon, Naples, Seville) but not that much in northen European cities (London, Paris, Brussels).

However, the extreme warming scenario RCP8.5 2070-2099 will impact most investigated European cities significantly with growing water scarcity issues. Even cities as London, Budapest, Brussels, Bucharest, Munich and Toulouse are projected to experience water scarcity.

Thus, many urban areas in Europe are projected to experience longer and intenser water scarcity - indicated by WEI+ - but at the same time to experience increases in annual runoff.

8 Adaptation measures

In the ongoing BLUE2 research project, we did some simulations with the following measures, based on reported planned investments until 2027 by EU memberstates under the Water Framework Directive:

- Increasing irrigation efficiency by changing method (e.g sprinkling to drip); Sub-optimal irrigation strategies may lead to only limited reductions of crop yield, but with substantial water savings; this measure may likely only feasible when irrigation water has a price
- Reduce leakage in the public water supply network; this is an expensive operation, and may only be feasible in water scarce regions.
- Shifts from conventional energy production (coal) to renewable energy production (wind, solar, hydropower) will also reduce the cooling water demand and net water consumption;
- Re-use of treated wastewater for irrigation

We will report on the results mainly in a separate report, but Figure 51 and Figure 52 summarize the results. Figure 51 shows that the combined 4 envisaged measures in EU MemberStates do relieve the water scarcity issues somewhat in the Mediterranean area, reducing the WEI+ with more than 0.2 in Spain.

However, when climate change is taken into account (the extreme RCP8.5 warming scenario), the effect of these measures are not much visible anymore. Milder climate change scenarios such as RCP4.5 will have less dramatic effects, but one might need to consider larger water saving efforts to keep water scarcity at bay in the Mediterranean.

Further water efficiency measures that could be considered are:

- Green cities (green roofs, parks) may lead to increased evapotranspiration in cities and reduced surface runoff, and therefore beneficial to reduce urban flooding
- More efficient cooling technologies might lead to a reduction of water use to produce energy;
- Water pricing for irrigation water, industrial water, and public water; this will create an incentive for users to consider water savings
- Multi-functional hydropower reservoirs. Hydropower reservoirs may stop producing energy during parts of the year while shifting to other renewable energy (solar, wind) to enable the water being available for downstream irrigation or other usage at a later stage in the year. Also, the buffering of excess renewable energy production (e.g. wind) by pumped hydropower storage might be considered.

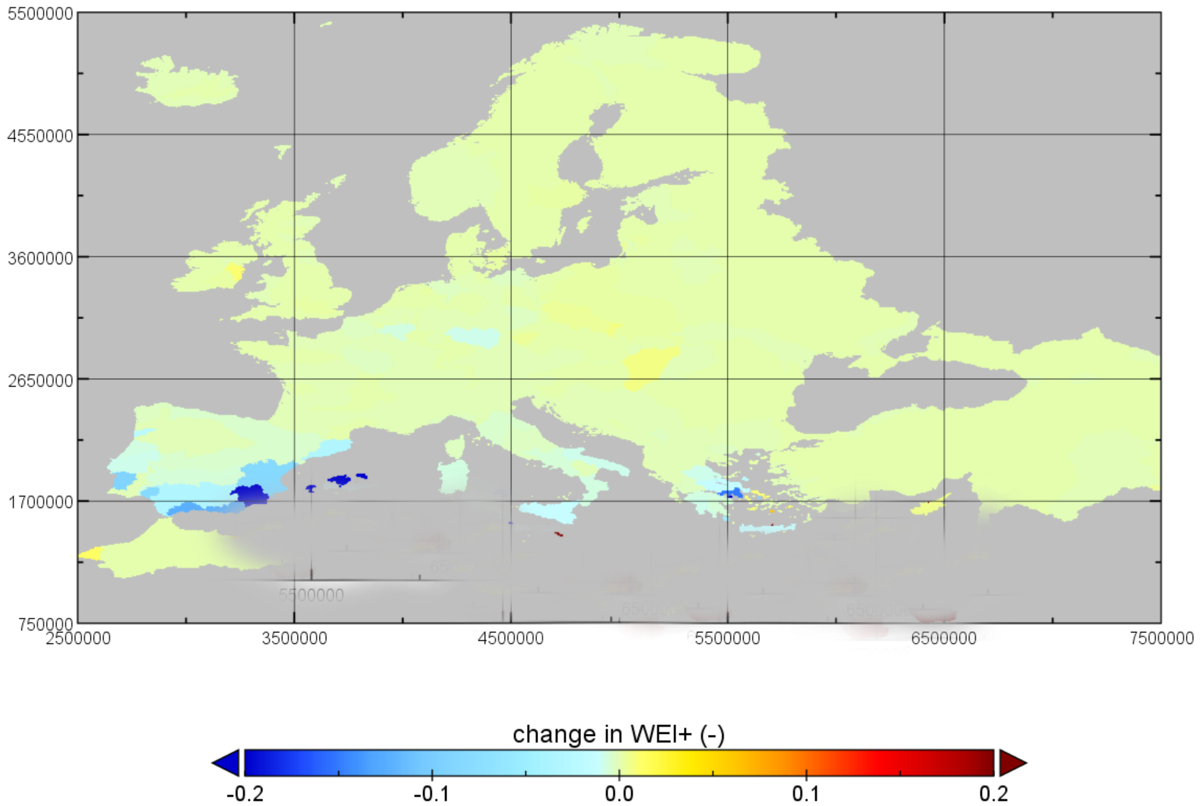

Figure 51 Combined effect of 4 water saving measures by EU-MS until 2027 on changes to the Water Exploitation Index (WEI+). Simulations of measures keeping the current climate.

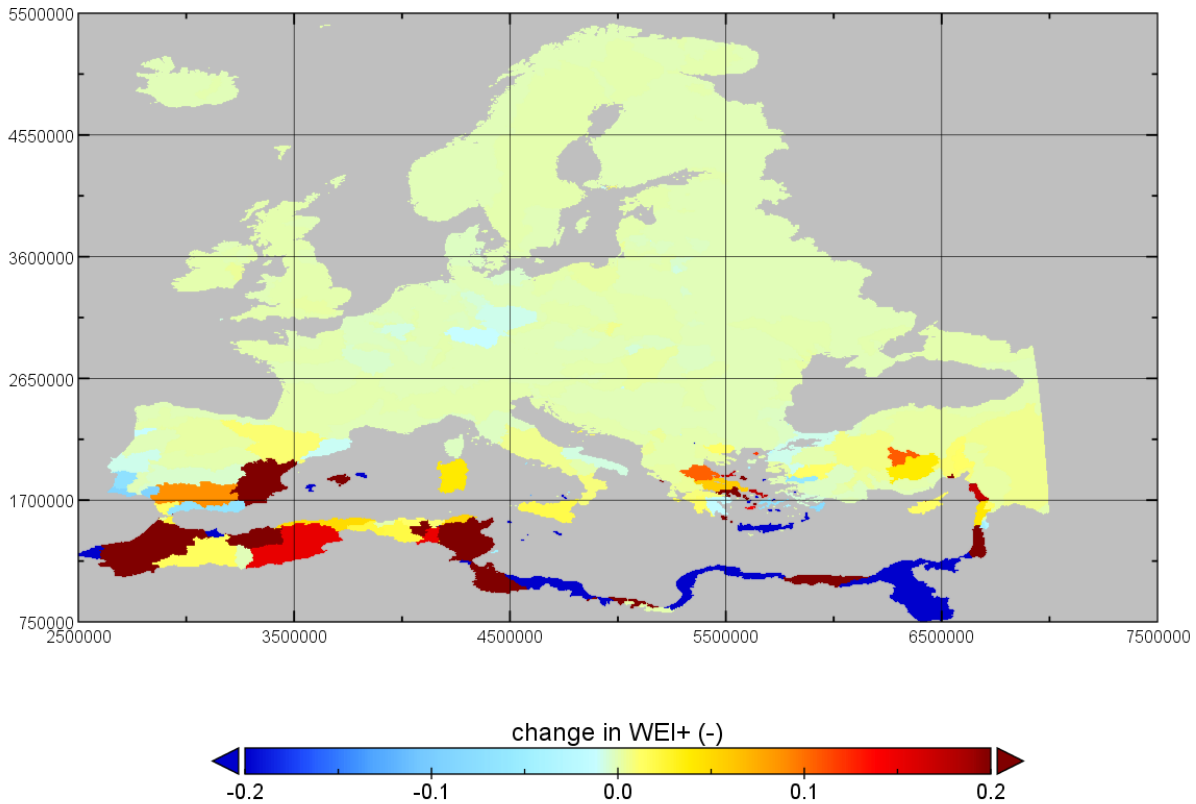

Figure 52 Combined effect of 4 water saving measures by EU-MS until 2027 on changes to the Water Exploitation Index (WEI+). Simulations including 2027 climate change under an RCP8.5 scenario.

9 Conclusions

Meeting the objectives of the Paris Climate Agreement of 2015 will lead to substantially less severe impacts for the water resources in Europe as compared to the impacts of climate change beyond 2 degrees global temperature increase. Especially summer water scarcity, flooding, cooling water availability, groundwater depletion, irrigation water availability, meteorological drought issues, hydropower issues, and environmental flow, are all considerably larger issues under exteme warming than under 2degree warming.

A North-South pattern emerges across Europe for water availability under a 2°C warming scenario. Overall, Southern European countries are projected to face increased water shortages, particularly Spain, Greece, Cyprus, Italy and Turkey.

The contribution of land use changes and water demand changes combined are in the order of 10-20%, whereas climate is responsible for 80-90% of the projected changes.

The severity of impacts under the 2°C warming scenario suggests that mitigation alone is not enough to avoid adverse climate change impacts; adaptation strategies such as water savings and efficiency measures will be needed too.

SURFACE WATER AVAILABILITY

The results of the water resources impact simulation under a 2°C warming scenario, including climate change, land use change and water demand changes show a North-South pattern across Europe for water availability. Overall, Southern European countries are projected to face decreasing water availability, particularly Spain, Portugal, Greece, Cyprus, Malta, Italy and Turkey. Central and Northern European countries show an increasing annual water availability. The extremer RCP8.5 2070-2099 warming scenario displays the same spatial pattern as under the 2°C warming scenario, but more extreme in the amounts of increasing and decreasing water availability.

Seasonal analysis shows a marked differences between summer and winter streamflows, especially in France, Belgium and the UK. These three countries are projected to experience wetter winters and drier summers, with increased water availability in winter, and decreased water availability over the summer months. The extremer warming scenario shows again the same spatial pattern as under the 2°C warming scenario, but more extreme in the amounts of increasing and decreasing water availability

GROUNDWATER

Under a 2 degree warming scenario, Spain (-3272 Mm3/year), Portugal (-1080 Mm3/year), and Greece (-810 Mm3/year) are estimated to have significant reductions in groundwater recharge. The groundwater recharge reduction estimated for Spain - 3272 Mm3/year – is 15% of the reported annual amount of abstracted water for irrigation.

CURRENT PRESSURES ON WATER RESOURCES ARE EXACERBATED IN SOUTHERN EUROPE

The Water Exploitation Index (WEI+) is a metric that takes account net water consumption versus available renewable water resources. Values below 0.2 indicate areas without major water scarcity. Areas with values between 0.2 and 0.4 experience water scarcity in at least a part of the year. Areas with a WEI+ larger than 0.4 or often water scarce during a year. This indicator does take into account inflowing river water from cross-border river basins. According to this index, water scarcity is a regular issue already in some parts of Europe.

The water resources situation becomes more unsustainable under a 2°C warming scenario for countries in the Mediterranean, and especially Spain. Under the RCP8.5 end of the 21st century scenario, water scarcity would be even more widespread expanding even to central Europe. Overall, Southern European countries are projected to face increased water shortages.

WATER SCARCITY AFFECTED AREAS AND PEOPLE

Under an extreme warming scenario, the number of persons affected by water scarcity in EU28 countries could increase at the end of the 21st century from the current 85 million to 104 million (Mediterranean - robust) or potentially 295 million (EU28 - less robust). Under the 2°C warming period it is projected that the number of affected people increases slightly from 85 to 94 million persons, mainly in the Mediterranean countries.

If water demand stays at current usage levels and without significant water saving efforts, the warming climate and reduced precipitation in the Mediterranean causes extreme increases in water scarcity. The people already affected under current climate will encounter much intenser water scarcity than at present.

RUNOFF IN CITIES

Local runoff production is increasing under the 2°C warming scenario as a consequence of climate change and urban expansion. This could cause local water excess problems and sewer overflows. Most likely many urban areas are projected to be more vulnerable for pluvial flooding in a future climate. Some Mediterranean cities, such as Lisbon and Seville are projected to have decreased annual runoff.

SOIL MOISTURE STRESS

Under a 2 degree warming scenario, there is a tendency of increased soil moisture stress in large parts of Europe, including France and UK. Areas which are currently already often stressed in the Mediterranean will become even more stressed under the 2°C warming scenario.

HIGH FLOWS

For autumn and winter months, the projections indicate increased high flows almost everywhere in Europe, with river discharges at that frequency increasing by 10-30%. The springtime months show a decrease in high flows around the Baltic Sea, very likely related to decreasing snow amounts under a warmer climate, and thus less problems with snowmelt floodings. The summer months especially show increased high flows in Central and Eastern Europe.

Under the extreme warming scenario, the projected changes indicate the same spatial pattern of high flow changes as under the 2 degree warming, but the magnitudes of the flows are more extreme.

LOW FLOW

The projections for low flow conditions under a 2 degree climate together with projected land use and water demand change or Europe show again the North-South pattern, with typically increased low flow and drought issues in the Mediterranean countries.

HYDROPOWER

We project for the 2-degree climate change a 4% decrease of hydropower annual inflow for the SW European region, consisting of Spain, Portugal, Southern France and Northern Italy. A 2% reduction is projected for the SE European region, consisting of the Balkans, Greece and Southern Italy. However, both decreases and increases are projected within these regions. For NE Europe, we project increases for hydropower locations with around 13%, potentially leading to local dam safety issues.

For the end of the century RCP8.5 climate, we do project a far more extreme picture, with 12% decreases in hydropower inflow in the SW European region (Spain, Portugal), and 10% decreases in the SE region (Greece, Balkans). For NE Europe, we project increases for hydropower locations with around 28%, potentially leading to dam safety issues.

COOLING

We project significant decreases of low flows of around 25% in the SW European region (Spain, Portugal, Southern France, parts of Italy) and also in the SE European region (Greecse, Southern Italy, Balkan countries). This might lead to cooling water availability issues for termal power stations, in addition to the higher temperature of the cooling water under the warming scenarios. For Scandinavian countries and Eastern European countries the low flows are improving.

THE NEED FOR ADAPTATION

The severity of some of the projected changes in water availability presented here, which are under a global warming scenario in line with the Paris Agreement, suggests that various adaptation mechanisms will be needed to lessen the effects of climate change on European water resources, even under a 2°C warming scenario.

Projected increases in water dependency for some regions calls for sustained water diplomacy between countries as well as international multi-member-state management of river basin water resources. In Europe, this is already foreseen under the Water Framework Directive.

A number of planned adaptation strategies could be targeted at irrigation practices to lower pressures on water resources. Water pricing for irrigation water, as well as for industrial water, and public water, could create an incentive for users to consider water savings. Irrigation efficiency could be increased by changing irrigation methods (e.g from sprinkling to drip irrigation), but this is likely to only be feasible when irrigation water has a price. Furthermore, sub-optimal irrigation strategies may lead to only limited reductions in crop yields, but towards substantial water savings.

Other options might focus on delivering more efficient cooling technologies that lead to a reduction in water use for producing energy. In addition, shifts from conventional energy production (coal) to renewable energy production could reduce cooling water demand and net consumption.

Some of these measures are to some extent being implemented by European Memberstates within the Water Framework Directive. However, preliminary analysis suggests that planned MS measures on water efficiency improve the state of water resources under current climate, but may not be sufficient under a climate warming scenario.

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List of abbreviations and definitions

CORDEX	CoORdinated Downscaling EXperiment
EC	European Commission
EU	European Union
EDO	European Drought Observatory
EFAS	European Flood Awareness System
FAO	Food and Agricultural Organisation
GDP	Gross Domestic Product
GVA	Gross Value Added
JRC	DG Joint Research Centre of the European Commission
LISFLOOD	Name of water resources model used here, developed at JRC. Part of a group of hydrological models (LISEM, LISFLOOD, LISFLOOD-FP, LISQUAL, LISCOAST, LISENGY) developed using grid based techniques since 1991)
LU	Land Use
LUISA	Land Use Integrated Sustainability Assessment platform
NUTS	Nomenclature of Territorial Units for Statistics
Q5	5^{th} percentile of river discharge, used as low flow indicator
Q10	10^{th} percentile of river discharge, used as low flow indicator
Q50	50^{th} percentile of river discharge ~ median streamflow
Qmean	Average river discharge or streamflow
Q95	95^{th} percentile of river discharge, used as high flow indicator
Q995	99.5^{th} percentile of river discharge, used as flood hazard indicator
RCP	Representative Concentration Pathways, greenhouse gas emissions scenarios
RWS	Root Water Stress Index
Water Abstraction	Actual abstracted water from surface or groundwater resources
Water Consumption	Net consumed or evaporated water amount (abstraction minus return flow)
Water Demand	Absolute demand of water from the sectors; if no water availability limitations exist, demand is similar to the abstracted amount
Water Use	Term that is preferably to be avoided to prevent confusion, since it is often not clear if gross withdrawls are meant or gross water demand or net (actual) consumption
Water Withdrawls	Another term for 'Water Abstraction'; identical meaning
WD	Water Demand
WDI	Water Dependency Index: Index between 0 and 1 indicating the dependency of a region for its water on upstream regions to fulfil the local water demand of the region

WEI+	Water Exploitation Index (Plus): Index between 0 and 1 indicating water consumption versus water availability, including inflowing water from upstream regions. Sometimes also indicated as WeiC (WEI consumption). Definition agreed upon in the EU Working Group on Water Scarcity and Droughts around 2011.
WEI	Water Exploitation Index (without the plus): refers to water abstraction as a fraction of water availability. These values are typically substantially higher than WEI= values
WS	Water Scarcity

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