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FUTURE PROJECTIONS OF WATER SCARCITY IN THE DANUBE RIVER BASIN DUE TO LAND USE, WATER DEMAND AND CLIMATE CHANGE

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Abstract

This paper presents a state-of-the-art integrated model assessment to estimate the impacts of the 2°C global mean temperature increase and the 2061-2090 warming period on water scarcity in the Danube River Basin under the RCP8.5 scenario. The Water Exploitation Index Plus (WEI+) is used to calculate changes in both spatial extent and people exposed to water scarcity due to land use, water demand, population and climate change. Despite model and data uncertainties, the combined effects of projected land use, water demand and climate change show a decrease in the number of people exposed to water scarcity during the 2°C warming period and an increase in the 2061-2090 period in the Danube River Basin. However, the projected population change results in a decrease of exposed people in both warming periods. Regions with population growth, in the northwestern part of the Danube River Basin experience low water scarcity or a decrease in water scarcity. The largest number of people vulnerable to water scarcity within the Danube River Basin are living in the Great Morava, Bulgarian Danube and Romanian Danube. There, the combined effects of land use, water demand and climate change exacerbate already existing water scarce areas during the 2°C warming period and towards the end of the century new water scarce areas are created. Although less critical during the 2°C warming period, adjacent regions such as the Tisza, Middle Danube and Siret-Prut are susceptible to experience similar exposure to water scarcity within the 2061-2090 period. Climate change is the most important driver for the increase in water scarcity in these regions, but the strengthening effect of water demand (energy sector) and dampening effect of land use change (urbanization) does play a role as well. Therefore, while preparing for times of increased pressures on the water supply it would be advisable for several economic sectors to explore and implement water efficiency measures.

Keywords: Danube river basin, water scarcity, global warming, land use change, water demand change, population change

INTRODUCTION

Growing human water demands due to population growth in many region of the world, socio-economic developments and climate change causes pressures on our freshwater resources. It is expected that the water supply cannot fulfil the water demands in coming decades (Vörösmarty et al., 2000; Stahl, 2001; Lehner et al., 2006; Alcamo et al., 2007; Arnell et al., 2011, 2013; Sperna Weiland et al., 2012; Gosling and Arnell, 2013; Hanasaki et al., 2013; van Vliet et al., 2013; Arnell and Lloyd-Hughes, 2014; Haddeland et al., 2014; Prudhomme et al.,2014; Schewe et al., 2014; Schlosser et al., 2014; Wada et al., 2014; Kiguchi et al., 2015), which means that water scarcity is rapidly increasing in many regions.

For Europe, water scarcity and drought events got special interest following the droughts in 2003 (ICPDR, 2015), which reflected the projected temperature extremes for future summers (Beniston, 2004). For transboundary rivers, like the Danube River Basin (DRB), river basin management is important as sharing water resources in times of future drought and water scarcity creates interdependencies that may lead to both sectoral and regional water conflicts (Farinosi et al., 2018). The DRB covers 10% of the territory of continental Europe with 80 million people in 19 countries (ICPDR, 2015; Malagó et al., 2017; Karabulut et al., 2016). Therefore, it is important to find a good balance between water availability and water demand for a wide range of sectors, such as irrigation, livestock, energy and cooling, manufacturing industry, navigation, as well for domestic uses. The water-energy-food-ecosystem (WEFE) nexus is a novel way to address these interlinked and often simultaneously water allocation strategies. Although not top priority yet, river basin management in the DRB, coordinated by the International Commission for the Protection of the Danube (ICPDR), is expected to become more important in future climate (ICPDR, 2015).

In present climate, potential water scarcity is predominantly appearing in the Pannonian Danube, in some subbasin of the Tisza, Middle Danube and Lower Danube (Karabulut et al., 2016; ICPDR, 2013). In addition, densed populated urban areas and areas with low natural water yield are also susceptible for localized water scarcity (Karabulut et al., 2016). Water stress is projected to increase in the southern and eastern parts of the DRB, especially in smaller tributary rivers due to a lack of summer precipitation (ICPDR, 2013, 2018). Although important to keep up with growing demands, human interventions, like reservoirs and water transfers, or other factors such as social, demographic, and economic development are not considered in most of these water resources modelling studies. Recent improved details in water use scenarios (Bernhard et al., 2018a, 2018b) and the availability of land use projections (Jacobs-Crisioni et al., 2017) open new opportunities for an integrated assessment of future climate, land use change and water consumption in relation to water resources.

The aim of this study is to provide a state-of-the-art integrated model assessment in relation to water scarcity in the DRB under global warming which is of high interest to inform and support climate policy makers for mitigation and adaptation strategies. In addition to the integrated impacts, the isolated impacts of land use, water demand and climate change will be examined.

METHODOLOGY

Hydrological model

LISFLOOD is a GIS-based spatially-distributed hydrological rainfall-runoff model (De Roo et al., 2000; Van der Knijff et al., 2010; Burek et al., 2013). Most hydrological processes in every grid-cell defined in the modelled domain are reproduced and the produced runoff is routed through the river network. Although LISFLOOD is a regular grid-based model with a constant spatial grid 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, forest area, paddy rice irrigated area, crop irrigation area and other land uses. 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.

LISFLOOD is successfully applied for applications for flood forecasting (Thiemig et al., 2015; Bisselink et al., 2016; Alfieri et al., 2013; Emerton et al., 2018) as well for studies dealing with climate change impact assessments in terms of water resources (Bisselink et al., 2018), streamflow drought (Forzieri et al., 2014), flood risk (Alfieri et al., 2015, 2017; Dottori et al., 2017) and multi-hazard assessments (Forzieri et al., 2016).

For this work, LISFLOOD was run on the Danube domain at 5km spatial resolution and daily time step. The results of this study are based on the Water Exploitation Index Plus (Wei+) indicator (Faergemann, 2012), which is a water scarce indicator. The WEI+ is determined at monthly timescale and in subregions (typically subriver-basins within a country) to avoid averaging skewed results. For uniformity, both the input and output maps presented here are area-averaged for every single subregion. More details on the model setup can be found in Burek et al. (2013).

Climate projections

The climate scenarios used in this study were produced within the EURO-CORDEX initiative (Jacob et al., 2014). 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 the 21st century. The climate projections considered in this work are listed in Table 1 and are all based on RCP8.5 (Riahi et al., 2011). The RCP8.5 scenario represents a situation in which emissions continue to increase rapidly (worst case scenario), and typically exceed 3^{o}C warming before the end of the current century. From each climate projection meteorological variables were extracted for historical and future climate scenarios and used to estimate daily evapotranspiration maps with the Penman-Monteith equation. These maps together with bias-corrected temperature and precipitation (Dosio et al., 2012) were then used as input for LISFLOOD.

From LISFLOOD's output we analysed the 30-year periods centered on the year of exceeding the global-mean temperature of 2^{o}C according the used Global Climate Model (GCM; Table 1) and the time window 2061-2090. To represent the present climate scenario, simulations from the period 1981-2010 are performed and analysed as well.

Table 1 EURO-CORDEX climate projections used in this study and corresponding year of exceeding 2^{o}C warming with the 30-year evaluation period.

	Institute	GCM	RCM	2^{o}C	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	2035	2021-2050
7	SMHI	EC-EARTH	RCA4	2041	2027-2056
8	SMHI	CNRM-CM5	RCA4	2044	2030-2059
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

The DRB is approximately 802,525 km^2 large and located in Central and Southeast Europe. The ICPDR divides the DRB in 15 water management regions (Fig. 1a), mostly subbasin catchments with area ranging from approximately 13650 km^2 (Delta-Liman) to 149450 km^2 (Tisza). The results of this study will be presented based on these water management regions. The DRB explores various climate regimes due to its vast area and topographic variability and can be categorized in four climate regimes with an aridity index ranging from 0.2-0.5 (semi-arid), 0.5-0.65 (dry-subhumid), 0.65-0.80 (moderate humid), to > 0.80 (humid). The aridity index is the ratio of ensemble mean of the precipitation and potential evapotranspiration from the climate projections (Table 1). Figure 1 shows the spatial distribution of climatological aridity of both present and future climate. The derived aridity index for present climate (1981-2010) indicates that 8.6% of the total DRB area can be classified as semi-arid located in the southeastern part of the DRB surrounded by the dry-subhumid regions (22.4%) in the southeastern and middle part of the DRB with a continental climate. The moderate humid (20.2%) and humid regions (48.8%) are located in mountainous areas or in areas influenced by the Atlantic climate.

Many studies provide climate projections with temperature, precipitation and evapotranspiration trends (Stagl and Hattermann, 2015; Jacob et al., 2014; Hlásny et al., 2016; Bartholy et al., 2014; ICPDR, 2013; Laaha et al., 2016; Pieczka et al., 2011). In short, the air temperature is likely to increase in future with a gradient from northwest to southeast. Overall, small precipitation changes are to be expected as the DRB is located in a north-southern transition zone between increasing (northern part of DRB) and decreasing (southern part of DRB) future precipitation. Moreover, seasonal behavior of extreme temperature and precipitation is likely to be more pronounced with an increasing number of extreme precipitation events in winter and more dry spells in summer. These change in precipitation and potential evapotranspiration associated with warming temperatures lead to an increasing aridity of the semi-arid regions in both the 2^{o}C warming period (+1.4%) and 2061-2090 period (+4.5%) whereby the spatial extent is growing over time towards southwest direction (Fig. 1a) on the expense of the dry-subhumid regions which decrease in spatial extent with -3.1% and -2.3% respectively (Fig. 1b). The spatial extent of both the moderate humid and humid regions are increasing with 1.0 % and 0.7% respectively between present climate and the 2^{o}C warming period with the largest increase in the Pannonian Danube (Fig 1c,d), but the spatial extent of the humid and humid regions is decreasing again towards the end of the century (2061-2090) with respectively -0.8% and -1.3%.

From the 15 water management regions, the Austrian Danube, Morava, Vah-Hron-Ipel, Pannonian Danube, Drava, Sava and Tisza shift towards a wetter climate regime, while the Middle Danube, Great Morava, Bulgarian Danube, Romanian Danube and Siret-Prut tend to shift towards a drier climate regime under 2^{o}C global warming. Towards the end of the century (2061-2090), some additional regions show a tendency towards a drier regime, like the Tisza and Sava. The Vah-Hron-Ipel and Pannonian Danube regions show an increase in spatial extent of the semi-arid areas, but also an increase in spatial extent of the humid regions. Only the spatial extent of the Morava region continues growing towards a wetter

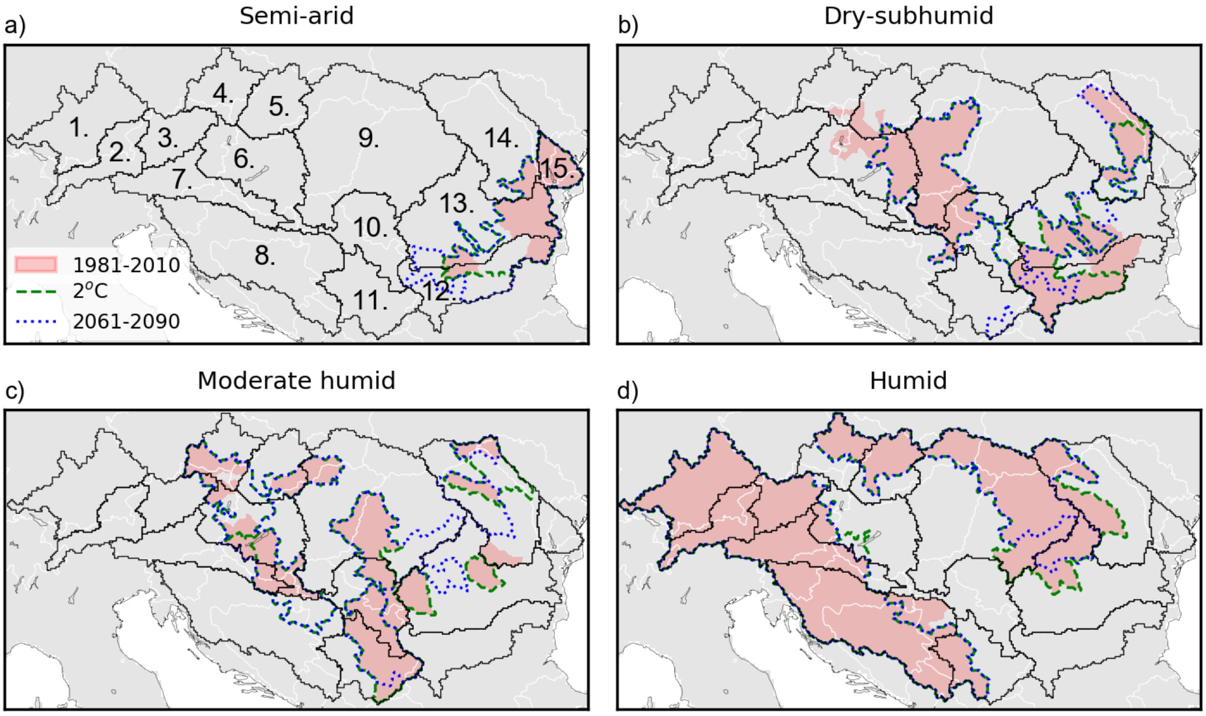

Fig 1 Spatial distribution of a) Semi-arid, b) Dry-subhumid, c) Moderate humid, and d) Humid regions for the baseline 1981-2010, 2^{o}C and 2061-2090 warming periods based on the ratio of the ensemble mean of the precipitation and evapotranspiration. In figure 1a the 15 ICPDR water management regions are inserted: 1. Upper Danube, 2. Inn, 3. Austrian Danube, 4. Morava, 5. Vah-Hron-Ipel, 6. Pannonian Danube, 7. Drava, 8. Sava, 9. Tisza, 10. Middle Danube, 11. Great Morava, 12. Bulgarian Danube, 13. Romanian Danube, 14. Siret-Prut and 15. Delta-Liman.

climate regime. Notice that the climate regimes of the Upper Danube, Inn and Delta-Liman regions remain unchanged in time where the first two are classified as humid and the latter as semi-arid.

Land use projections

The future land use projections used in this study are modelled using the JRC LUISA territorial modelling platform (Batista e Silva et al., 2013; Lavalle et al., 2011). LUISA translates socio-economic trends and policy scenarios into processes of territorial development. Among other things, LUISA allocates (in space and time) population, economic activities and land use patterns which are constrained by biophysical suitability, policy targets, economic criteria and many other factors. Except from the constraints, LUISA incorporates historical trends, current state and future projections in order to capture the complex interactions between human activities and their determinants. The mechanisms to obtain land-use demands are described in Baranzelli et al. (2014) and Jacobs-Crisioni et al. (2017). Key outputs of the LUISA platform are fine resolution maps (100 m) of accessibility, population densities and land-use patterns covering all EU28 member states expanded with Serbia, Bosnia Herzegovina and Montenegro until 2050. CORINE land use maps (Büttner and Kosztra, 2007) are used to cover the rest of the DRB. Although LISFLOOD normally operates on a substantially coarser resolution, the details of the LUISA output will remain for a large part due to the use of sub-grid fractions in LISFLOOD as explained in the 'Hydrological model' section. 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).

Figure 2 shows an example of projected changes of forest and urban land use classes based on the LUISA platform and used as input for LISFLOOD. In general, an increase of the forested area is projected for the DRB (3%; Fig. 2a,c) with the most increase in the upstream regions and the Bulgarian Danube. The only regions without change in forested area are the Middle Danube, Great Morava and the Delta-Liman region. On average, all the selected regions show an increase in urban land use with the most pronounced increase in the Inn catchment (24%) due to the urbanization in South Germany (Fig. 2b,d). Minor or no changes are projected for the rural areas (Fig. 2b).

Water demand projections

Water demand in LISFLOOD consist of five components from which the irrigation water demand is estimated dynamically within the model as it is driven by climate conditions. The irrigation water demand with a distinction in simulation methods for crop irrigation and paddy rice irrigation is described in Bisselink et al. (2018).

The other four external sectoral components are (manufacturing) industrial water demand, water demand for energy and cooling, livestock water demand and domestic water demand. In general, water use estimated for these four sectors are derived from mainly country-level data (EUROSTAT, AQUASTAT) with different modelling and downscaling techniques as described in Vandecasteele et al. (2014). Output of the LUISA

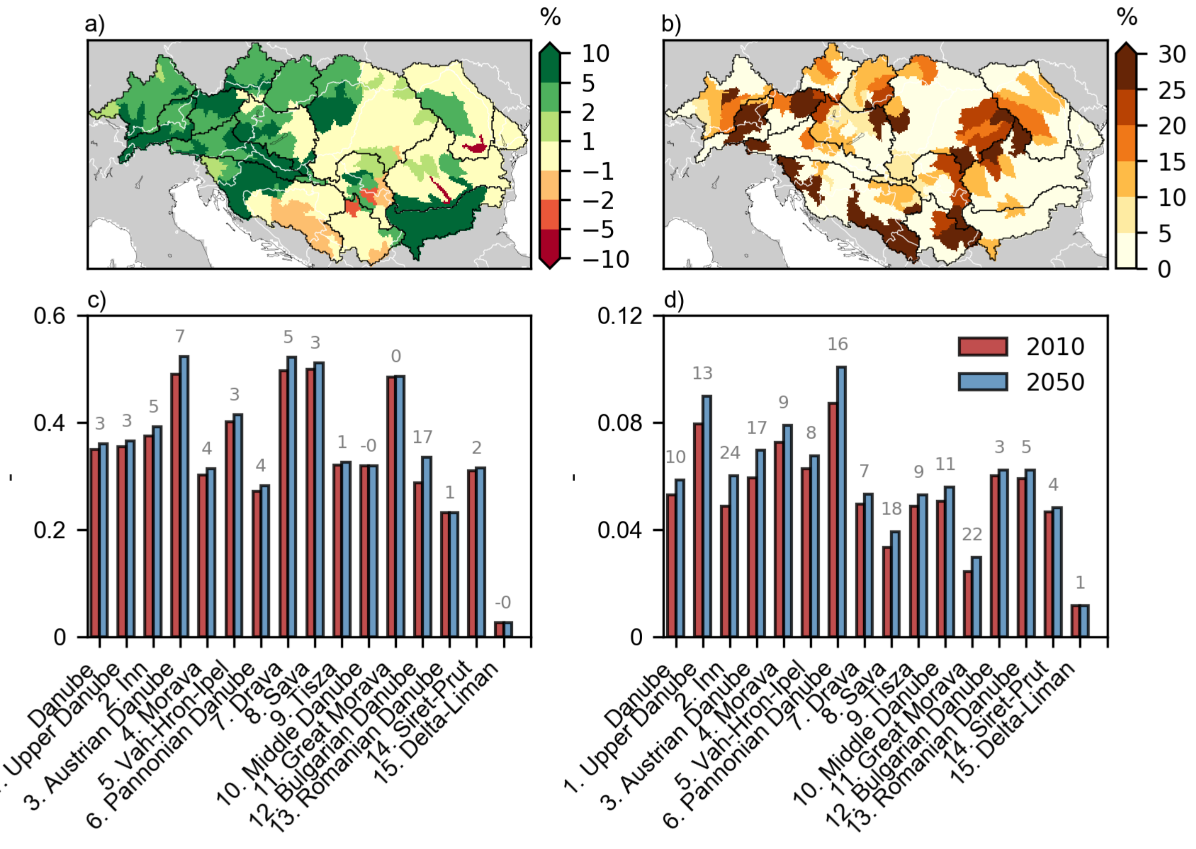

Fig 2 a) Projected change (%) in a) forest fraction, and b) urban fraction between 2010 and 2050. Barplot of area-averaged fractions (-) for c) forest and d) urban area for 2010 and 2050 for the selected regions in the DRB. The grey numbers above the bars indicate the projected change (%) between 2010 and 2050.

platform is used for the spatial downscaling of both present and future water use trends to ensure consistency between land use, population and water demand. A brief description of each sectoral component is given below. Livestock water withdrawals are estimated by combining water requirements from literature with livestock density maps for cattle, pigs, poultry, sheep and goats. The methods are described in detail by Mubareka et al. (2013).

For the energy and cooling demand, national water use statistics 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).

Industrial water demands are based on country-level figures from national statistics offices for the total water use by manufacturing industries, mining and construction. Future industrial water use trends are simulated based on Gross Value Added (GVA) projections from the GEM-E3 model to represent industrial activity and an efficiency factor to represent improving water efficiency due to technical developments (Bernhard et al., 2018a). Since the GEM-E3 model only provide projections for the EU28, industrial water use projections are assumed constant for countries outside EU28.

Water demands for the household sector are derived from a specific household water usage module (Bernhard et al., 2018b) which simulates water use per capita based on socio-economic, demographic and climate variables.

This model was based on collected data at NUTS-3 from 2000-2013 for all EU28 countries on household water use, water price, income, age distribution 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. Socio-economic, demographic and climate projections are used to estimate future domestic water use per capita. The future projections of both the industrial and domestic water demand are calculated every 5 years until 2050. For the years in between the 5yr-window a linear growth is assumed.

Figure 3 shows a map of the projected change in total water demand between 2010 and 2050 for all water usages excluding (irrigated) agriculture. The total water demand is increasing between 2010 and 2050 in the DRB (Fig. 3a) with the largest relative change in the Romanian Danube. The largest absolute water demand change is observed in the Pannonian Danube (Fig. 3b) following the urban land use change with expanding cities like Vienna and Budapest (Fig. 2d). The water demand for energy and cooling is the largest contributor to the water demand change.

Population projections

Population projections are based on EUROSTAT and are constraints for the LUISA model (Batista e Silva et al., 2013). In Figure 4 the population change between 2010 and 2050 is presented. The population is increasing in urban areas in the northwestern part and decreasing in the more rural eastern and southeastern part of the DRB (Fig. 4a). Overall, the population in the entire DRB is decreasing with 6% with the largest relative decrease in the Bulgarian Danube (Fig. 4b). The Pannonian Danube is one of the few regions with a future population growth (14%) resulting in an increase in both urban areas (Fig. 2d) and water demand (Fig 3b).

RESULTS

Changes in water scarcity

To estimate future changes in water scarcity we used here the WEI+ indicator (Faergemann, 2012), which is defined as the ratio of the total water net consumption divided by the freshwater resources of a region, including upstream inflowing water. WEI+ values have a range between 0 and 1, with values between 0-0.1 denote “low WS”, “moderate

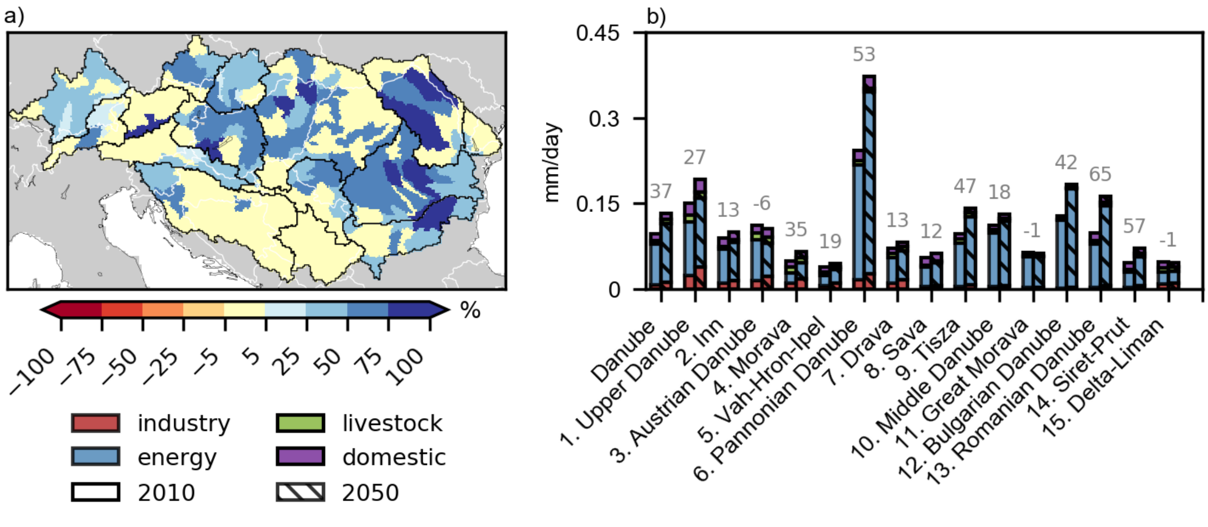

Fig 3 a) Projected change (%) of aggregated total water demand (livestock, energy production and cooling, industry, households and public sector) between 2010 and 2050, and b) barplot of area-averaged aggregated total water demand (mm/day) for 2010 and 2050 for the selected regions in the DRB. The grey numbers above the bars indicate the projected change of the aggregated total water demand (%) between 2010 and 2050.

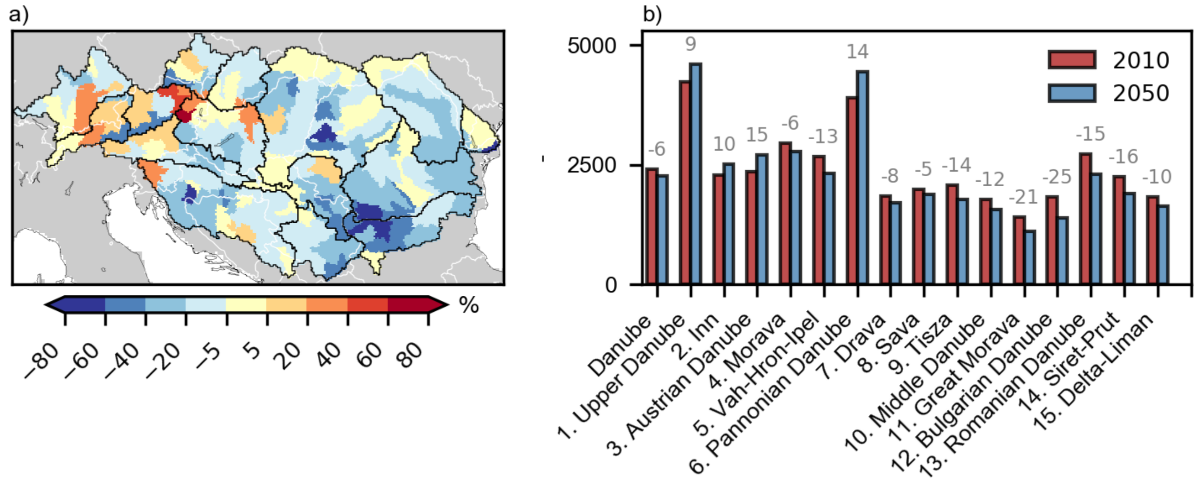

Fig 4 a) Projected change (%) in population between 2010 and 2050, and b) barplot of area-averaged population for 2010 and 2050 for the selected regions in the DRB per 25 km^2 grid. The grey numbers above the bars indicate the projected change (%) between 2010 and 2050.

WS" if the ratio lies in the range 0.1-0.2, "WS" when this ratio is in the range of 0.2-0.4, and "severe WS" if the ratio exceeds the 0.4 threshold.

First we consider the spatial pattern of the change in water scarcity days in a year for the 2°C warming period relative to present climate under RCP8.5 (Fig. 5). The DRB can be divided in three categories:

1. Regions which shift towards less water scarcity days in a year (i.e. increase in 'low WS' and decrease in 'moderate WS', 'WS' and 'severe WS') or remain unchanged: Upper Danube, Inn, Austrian Danube, Morava, Drava, Sava and Delta-Liman.
2. Regions which shift towards an increase in water scarcity days (i.e. decrease in 'low WS' and increase in 'moderate WS', 'WS' and 'severe WS'): Great Morava, Bulgarian Danube and Romanian Danube.
3. Regions including both water regions shifting towards less water scarcity days and water regions shifting towards an increase in water scarcity days (for e.g., the water region of a city): Vah-Hron-Ipel, Pannonian Danube, Tisza, Middle Danube and Siret Prut.

The most important change towards the end of the century (2061-2090) is that more regions are shifting towards an increase of water scarcity days with in the central part of the DRB (Vah-Hron-Ipel, Pannonian Danube and Sava) a shift from 'low WS' to 'moderate WS' and even a more pronounced shift in the Tisza, Middle Danube and Siret-Prut with an increase in 'WS' and 'severe WS' days. In the Great Morava, Bulgarian Danube and Romanian Danube the water scarcity days are exacerbating.

Population affected

Next, we put the water scarcity projections into a societal perspective to estimate how many people will be living in areas with 'moderate WS', 'WS' or 'severe WS' for at least 1 month within present climate, 2°C warming or 2061-2090 period. Figure 6 presents barplots of the individual regions with the number of people living for at least 1 month/30yr in 'moderate WS', 'WS' or 'severe WS' areas. The simulated 'moderate WS', 'WS' and 'severe WS' areas are overlaid with the population of the year 2010 and the projections of 2050 to quantify the contributions of solely the combined effect of land use, water demand and climate change (green dashed line) and the combined effect of land use, water demand and climate change together with population change (grey bar) respectively. The decrease or increase of the number of people living in 'moderate WS', 'WS' and 'severe WS' areas is not due to the population change if the grey bar and the green dashed line are at an equal population level. Note that, the number of people living for at least 1 month/30yr in 'low WS' areas is 100% for all regions and therefore this category is excluded. Moreover, the people living in the regions Upper Danube, Inn, Austrian Danube and Drava are never exposed to 'moderate WS', 'WS' or 'severe WS' longer than 1 month/30yr and therefore these regions are excluded.

The projections for the 2°C warming period in the DRB (Fig. 6a) show a decrease of people living in 'moderate WS', 'WS' and 'severe WS' areas compared to present climate due to the combined effect of land use, water demand and climate change together with population change. In general, the result of the DRB is also representative for the regions Vah-Hron-Ipel, Pannonian Danube, Tisza, Middle Danube, Great Morava and Siret-Prut (Figs. 6c,d,f,g,h,k). For the regions Morava, Sava and Delta-Liman (Figs 6b,e,l) the combined effect of land use, water demand and climate change is the only driver for the reduction of people living in 'moderate WS', 'WS' and 'severe WS' areas, while the decrease of the people living in 'moderate WS', 'WS' and 'severe WS' areas in the Romanian and Bulgarian Danube is almost solely due to the population change (Fig. 6i,j). Water scarcity is increasing in these regions as seen in the previous section but the people living in water scarce areas is decreasing which indicates that the areas affected by water scarcity are not growing. The areas which already experience water scarcity are projected to become more water scarce resulting in an equal or decrease in the number of people living in water scarce areas.

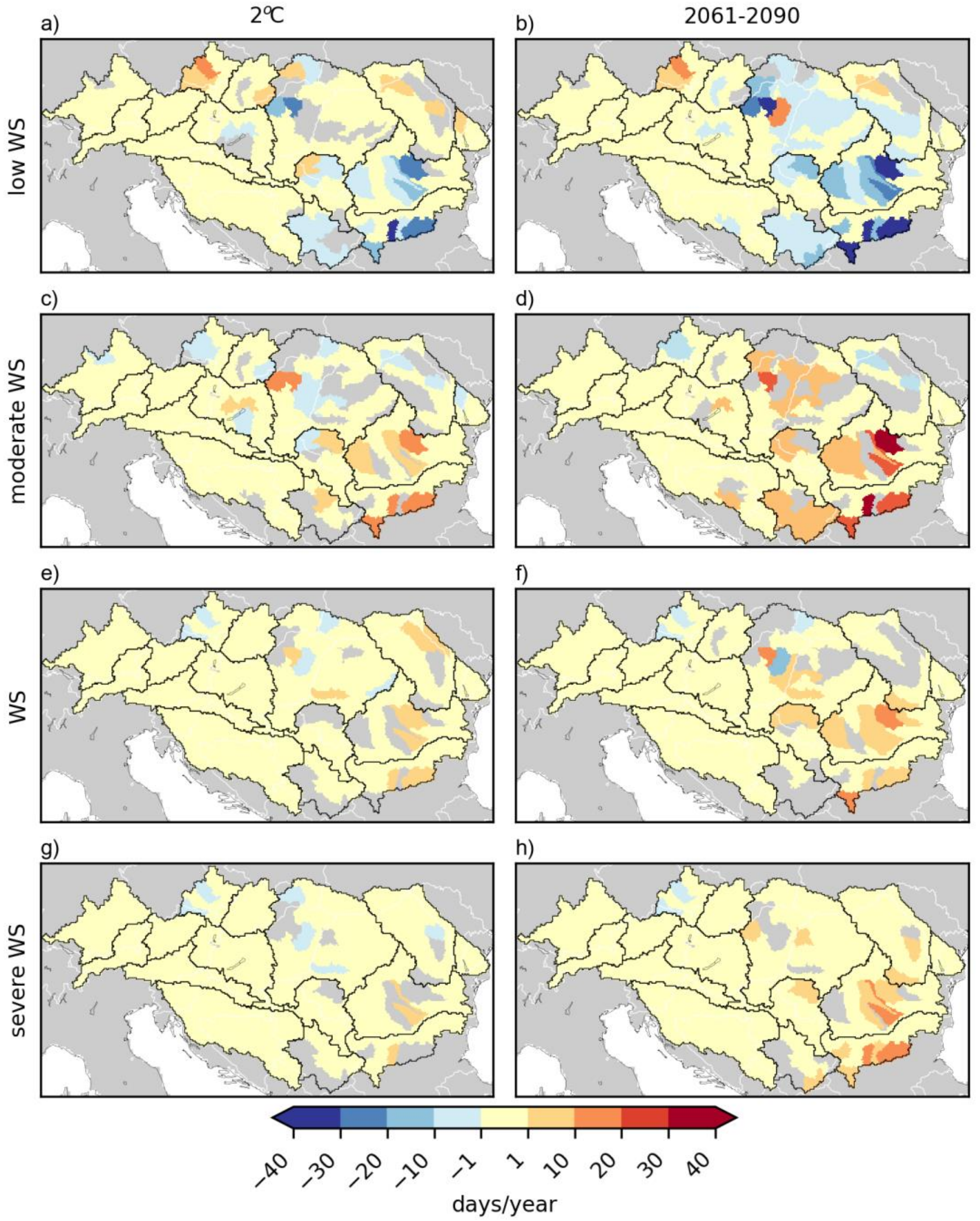

Fig 5 Projected change in days per year with 'low WS' (a,b), 'moderate WS' (c,d), 'WS' (e,f), and 'severe WS' (g,h) of the ensemble mean of the 2°C period (left panels) and 2061-2090 (right panels) relative to present climate (1981-2010). Grid cells within the DRB where not all models agree in the sign of change are greyed out. We consider the result valid if at least 7 out of 11 models agree in the sign of change (positive or negative).

For the 2061-2090 warming period, the water scarce areas in the DRB are expanding (see Fig. 5) and therefore an increase in people living in 'moderate WS', 'WS' or 'severe WS' areas is projected relative to the 2°C warming period (Fig. 6a). Compared to present climate, the number of people living in 'moderate WS', 'WS' or 'severe WS' areas are more or less equal again when only the combined effect of land use, water demand and climate change is considered but are still decreasing with the combined effect of land use, water demand and climate change together with population change (Fig. 6a). In more detail, this trend is also observed in a number of regions like: Tisza, Middle Danube, Great Morava, Bulgarian Danube, Romanian Danube and Siret-Prut (Fig. 6f,g,h,i,j,k). All these regions are projected to become just as or more water scarce in future in comparison to present climate but due to population change less people will be exposed to 'moderate WS', 'WS' and 'severe WS'. In the Sava region (Fig. 6e) the people living in both 'moderate WS' and 'WS' areas are increasing compared to present climate and 2°C warming period due to the combined effect of land use, water demand and climate change. In the Morava, Vah-Hron-Ipel, Pannonian Danube and Delta-Liman region (Fig. 6b,c,d,l) the people living in 'moderate WS', 'WS' or 'severe WS' areas remain unchanged or decreases compared to present climate due to land use, water demand and climate change only (Morava and Delta-Liman) or due to land use, water demand and climate change together with population change (Vah-Hron-Ipel, Pannonian Danube).

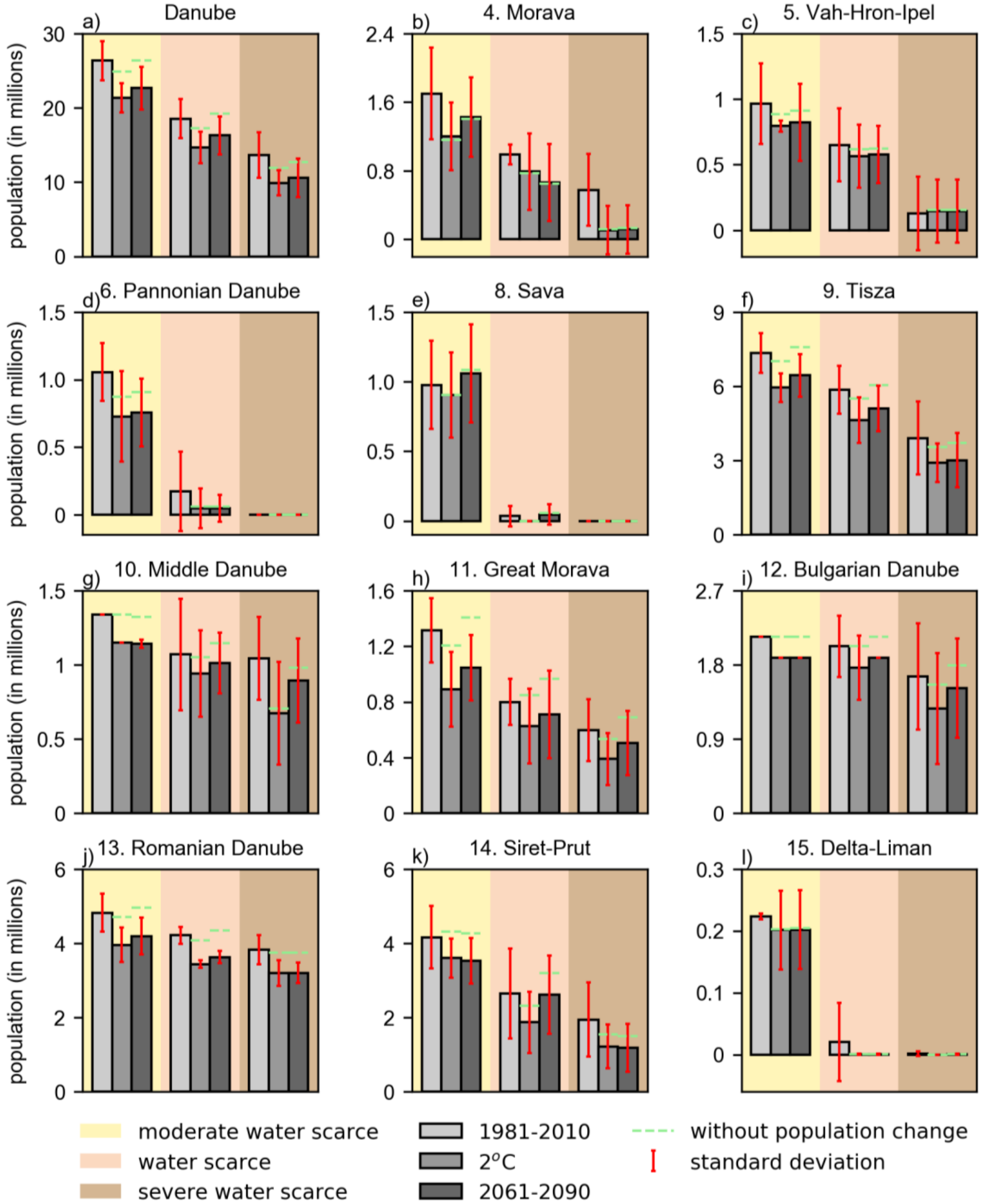

Fig 6 Barplot of population (in millions) located within water regions which have at least 1 month in the 30 year warming periods with 'moderate WS', 'WS' or 'severe WS' for the selected regions with and without taken the future population change (green dashed line) into account. Population data for 2010 is used for reference and 2050 for future projections. Error bars represent the ensemble standard deviation.

Impact of land use, water demand and climate change

The model simulations we performed in this study are an integrated assessment of land use, water demand and climate change (see section 'Methodology'). However, water resources can be considerable affected by the combined or isolated effect of land use, water demand and climate changes. Here, we attempt to quantify both the combined and isolated impact of land use, water demand and climate changes on the June-July-August (JJA) WEI+ by performing different combinations of simulations with/without land use or water demand together with climate changes. In Figure 7, the relative change between the JJA WEI+ of the ensemble mean of the 2°C warming period and present climate (1981-2010) is presented. The combined effect of land use, water demand and climate changes (Fig. 7a) on the JJA WEI+ show a decrease for water regions in the Morava, Tisza and Middle Danube, and an increase in the Great Morava, Bulgarian Danube, Romanian Danube and Siret-Prut. The most dominant impact on the JJA WEI+ change is climate change (Fig. 7b), but the land use (Fig. 7c) and water demand change (Fig. 7d) also contribute considerably in some water regions. In general, land use change has a negative effect while the water demand change has a positive effect on the JJA WEI+ change. For a more detailed illustration of

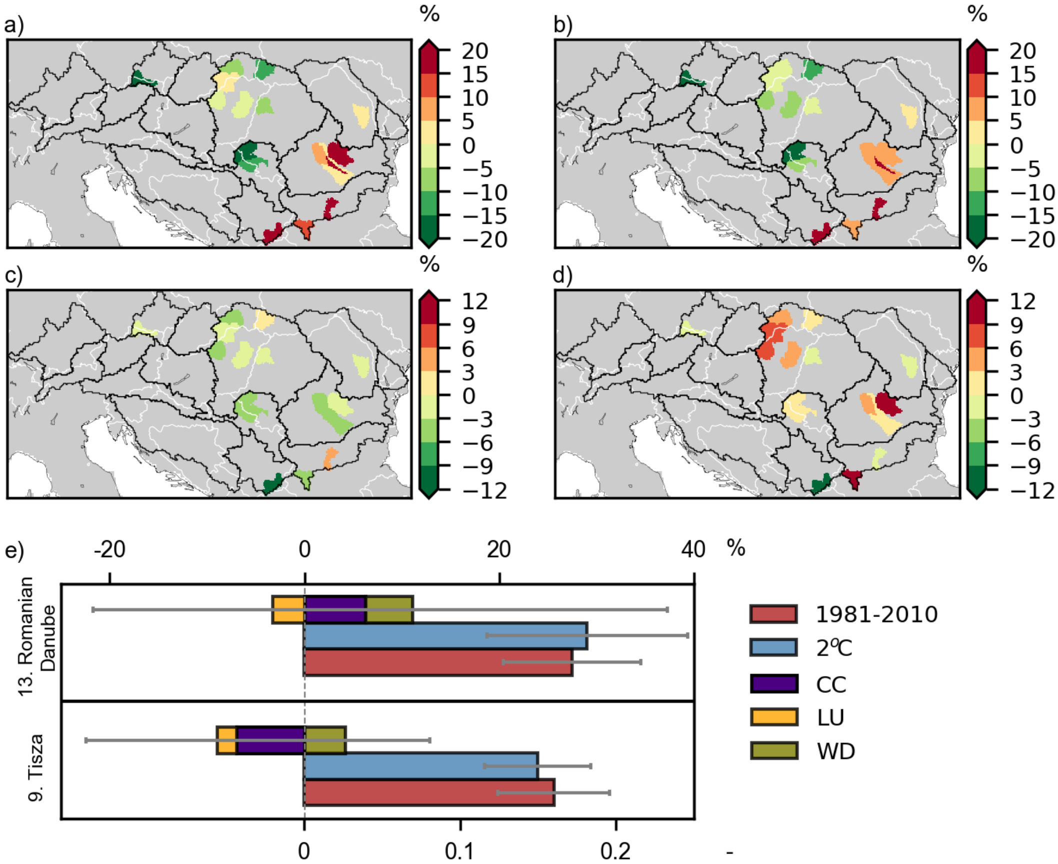

Fig 7 Projected relative change (%) between the JJA WEI+ of the ensemble mean of the 2°C warming period and present climate (1981-2010) from simulations including a) climate change, land use and water demand change, b) climate change only and the isolated effect of c) land use change and d) water demand change. Only water regions with an average WEI+ larger than 0.1 in present climate are selected e) Barplot of the contributions (%) of climate change, land use change and water demand change to the total change for present climate (1981-2010) and 2°C warming period including standard deviations for the selected regions.

this effect, the JJA WEI+ change and the isolated effect of land use, water demand and climate changes are presented in a barplot for the Tisza and the Romanian Danube (Fig. 7e). In the Romanian Danube an increase in JJA WEI+ between present climate and the 2°C warming period is observed due to climate change amplified by water demand change, while the land use change alleviates the increase of JJA WEI+. In contrast, in the situation where the JJA WEI+ is decreasing, like in the Tisza, the land use change is amplifying the decrease, while the water demand suppress this effect.

Uncertainties

Model studies with LISFLOOD, and modelling studies in general, go hand-in-hand with uncertainties. They are inextricable mainly caused by model structure or model parameterization due to for e.g. different precipitation sources (Bisselink et al., 2016). It becomes a major challenge when assessing the combined or isolated impacts of land use, water demand and climate change on water resources. The climate projections are accompanied by large uncertainties due to varying but plausible estimates of future warming. As the DRB is in a transition zone between a wetter and drier future climate, the models even disagree in the sign of change. Therefore, multiple climate projections are used to give us, at least, an estimate of the uncertainty. Unfortunately, a similar approach is not available for land use, population and water demand change. Overall, the uncertainty in land use, population, water demand and climate projections together with hydrological model parameterizations introduces considerable variability into the resulting projections of water scarcity. For this reason, the impact estimates of water scarcity and people exposed should be taken as an indication to which direction future scenarios evolves.

SYNTHESIS, DISCUSSION, AND CONCLUSION

In this study, we performed a state-of-the-art integrated model assessment including projections of land use, water demand and climate change to assess changes in water scarcity in the DRB under global warming. With the population projections we were able to estimate people exposed to low water scarcity (‘low WS’), ‘moderate WS’, ‘WS’ or ‘severe WS’. Moreover, different combinations of simulations with and/or without land use or water demand together with climate change allowed us to isolate the effect of land use, water demand and climate change in relation to water scarcity.

Changes in precipitation and potential evapotranspiration according to the mean of 11 climate projections reveal that semi-arid regions in both the 2°C warming period (+1.4%) and 2061-2090 period (+4.5%) are increasing in the DRB due to spatial expansion in the southeast part of the catchment. In the northwestern part we find a slight increase towards a more humid climate. These northwest to southeast gradient is in good agreement with the recently updated report of the ICPDR (ICPDR, 2018) and, in general, with the assessment of the change in water scarcity days. However, direct intercomparisons of projected water scarcity changes with other studies is not straightforward as, to our knowledge, this is the first attempt to integrate land use, water demand and climate change for future projections in the DRB.

People living in the DRB experience both increases and decreases in water scarcity in the future. Overall, this results in less people exposed to water scarcity (‘moderate WS’, ‘WS’ or ‘severe WS’) at the 2°C warming period, and more people towards the end of the century (2061-2090) when considering solely the combined effects of land use, water demand and climate change (i.e. population change excluded). In the ‘real world’ including population change even less people are getting exposed to water scarcity but not evenly distributed. The population is decreasing in the regions experiencing an increase in water scarcity while population is increasing in regions with a water scarcity decrease.

The Great Morava, Bulgarian Danube and Romanian Danube show a clear tendency towards an increase in water scarcity days between present climate and the 2°C warming period. However, this result is not reflected in the number of people exposed to water scarcity solely due to the combined effect of land use, water demand and climate change (i.e. population change excluded). So, although the combined effect of land use, water demand and climate change may not create new water scarcity areas, it may exacerbate water scarcity. Towards the end of the century (2061-2090), the combined effect of land use, water demand and climate change is creating new water scarcity areas which is reflected in the increase of population exposed to water scarcity at an equal or higher number compared to present climate again.

Opposite patterns, where the number of people exposed to water scarcity is stable or decreasing solely due to the combined effects of land use, water demand and climate change and not by population change, are observed for the Upper Danube, Inn, Austrian Danube, Morava, Drava, Sava and Delta-Liman regions for both the 2°C warming period and 2061-2090 period. In other regions, the projected water scarcity changes are very heterogeneous with areas with increasing and decreasing water scarcity in the same region. In the regions of Pannonian Danube and Vah-Hron-Ipel the change in people exposed to water scarcity is decreasing between present climate and the 2°C warming period and remains rather stable towards the end of the century. Water scarcity and the people affected in the regions Tisza, Middle Danube and Siret-Prut is decreasing due to the combined effect of land use, water demand and climate change together with population change at the 2°C warming period. At 2061-2090, the exposure to water scarcity is steeply increasing due to the combined effect of land use, water demand and climate change.

The isolated effect of land use, water demand and climate change proved that climate change is the most dominant driver for the water scarcity change. In June-July-August the water demand is also an important contributor for the change followed by the land use change. However, in other seasons the contribution of the water demand change is probably lower compared to the land use change. Anyhow, the growing water demand, mainly due to increase in energy use and subsequent cooling water usage, obviously puts pressure on the water supply resulting in amplifying water scarcity. Regions with increasing water scarcity exposure could mitigate towards renewable forms of energy production (solar) which might reduce the water needed for cooling and dampens the water scarcity increase.

Changes in hydrological cycle due to land use change are both positive and negative. Urban areas with more impervious surfaces upstream or in the water regions increase direct runoff towards the rivers, and hence the total volume of runoff in a water region resulting in tempering the water scarcity exposure, but may simultaneously decrease groundwater recharge, which is not included in the definition of the WEI+.

Although, population decrease ensures that less people are exposed to water scarcity, several sectors requiring water, such as rainfed and irrigated agriculture must adapt to reduced water availability at the risk of production loss or land degradation. These adaptation challenges are already needed in the short term for the Great Morava, Bulgarian Danube and Romanian Danube and in the long term also in the Tisza, Middle Danube and Siret-Prut.

The results obtained in this study showed that the complex interactions between land use, water demand and climate change requires an integrated model framework especially in combination with mitigation and adaptation measures involving several economic sectors. Further development in this direction is needed to tackle complex issues about water resources allocation and water scarcity problems.

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References

Alcamo, J., Flörke, M., Märker, M. 2007. Future long-term changes in global water resources driven by socioeconomic and climatic changes. *Hydrolog. Sci. J*. 52, 247–275. DOI: 10.1623/hysj.52.2.247.

Alfieri, L., Burek, P., Dutra, E., Krzeminski, B., Muraro, D., Thielen, J., and Pappenberger, F. 2013. GloFAS – global ensemble streamflow forecasting and flood early warning, *Hydrol. Earth Syst. Sci*. 17, 1161–1175. DOI: 10.5194/hess-17-1161-2013.

Alfieri, L., Burek, P., Feyen, L., Forzieri, G. 2015. Global warming increases the frequency of river floods in Europe. *Hydrol. Earth Syst. Sci*. 19, 2247–2260. DOI: 10.5194/hessd-12-1119-2015.

Alfieri, L., Bisselink, B., Dottori, F., Naumann, G., de Roo, A., Salamon, P., et al. 2017. Global projections of river flood risk in a warmer world. *Earths Future* 5(2), 171–182. DOI: 10.1002/2016ef000485

Arnell, N. W., van Vuuren, D. P., Isaac, M. 2011. The implications of climate policy for the impacts of climate change on global water resources. *Glob. Environ. Change* 21, 592–603. DOI: 10.1016/j.gloenvcha.2011.01.015

Arnell, N. W., et al. 2013. A global assessment of the effects of climate policy on the impacts of climate change. *Nat. Clim. Change* 3, 512–519. DOI: 10.1038/nclimate1793

Arnell, N. W., Lloyd-Hughes, B. 2014. The global-scale impacts of climate change on water resources and flooding under new climate and socio-economic scenarios. *Clim. Change* 122, 127–140. DOI: 10.1007/s10584-013-0948-4

Baranzelli, C., et al. 2014. The reference scenario in the LUISA platform – Updated configuration 2014 towards a common baseline scenario for EC impact assessment procedures. Report EUR 27019 EN, Luxembourg: Publications office of the EU.

Bartholy, J., Pongrácz, R., Pieczka, I. 2014. How the climate will change in this century? *Hungarian Geographical Bulletin* 63, 55–67. DOI: 10.15201/hungeobull.63.1.5

Batista e Silva, F., Gallego, J., Lavalle, C. 2013. A high-resolution population grid map for Europe, *J. Maps* 9, 16–28, DOI: 10.1080/17445647.2013.764830.

Beniston, M. 2004. The 2003 heatwave in Europe: A shape of things to come? An analysis based on Swiss climatological data and model simulations. *Geophys. Res. Lett.* 31, 2022–2026. DOI: 10.1029/2003gl018857

Bernhard, J., Reynaud, A., De Roo, A., Karssenberg, D., De Jong, S. 2018a. Household water use in Europe at regional scale: analysis of trends and quantification of main drivers, Under review.

Bernhard, J., Reynaud, A., De Roo, A., Karssenberg, D., De Jong, S. 2018b. Mapping industrial water use and water productivity levels in Europe at high sectoral and spatial detail, Under review.

Bisselink, B., Zambrano-Bigiarini, M., Burek, P., de Roo, A. 2016. Assessing the role of uncertain precipitation estimates on the robustness of hydrological model parameters under highly variable climate conditions. *J. Hydrol. Reg. Stud*. 8, 112–129, DOI: 10.1016/j.ejrh.2016.09.003.

Bisselink, B., Bernhard, J., Gelati, E., Adamovic, M., Jacobs, C., Mentaschi, L., Lavalle, C., De Roo, A. 2018. Impact of a changing climate, land use, and water usage on water resources in the Danube river basin, EUR 29228 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-79-85888-8, DOI: 10.2760/561327, JRC111817.

Burek, P., De Roo, A., van der Knijff, J. 2013. LISFLOOD – Distributed Water Balance and Flood Simulation Model - Revised User Manual. EUR 26162 10/2013; Publications Office of the European Union. Directorate-General Joint Research Centre, Institute for Environment and Sustainability, ISBN: 978-92-79-33190-9.

Büttner G, Kosztra B. 2007. CLC2006 Technical guidelines. Technical Report No. 17 / 2007. EEA. Available from http://www.eea.europa.eu/publications/technical_report_2007_17.

De Roo, A. P. J., Wesseling, C. G., Van Deursen, W.P.A. 2000. Physically-based river basin modelling within a GIS: The LISFLOOD model. *Hydrological Processes* 14, 1981–1992. DOI:10.1002/1099-1085(20000815/30)14:11/12<1981::AIDHYP49>3.0.CO;2-F

Dosio, A., Paruolo, P., Rojas, R. 2012. Bias correction of the ENSEMBLES high resolution climate change projections for use by impact models: Analysis of the climate change signal, *Journal of Geophysical Research D: Atmospheres* 117(17). DOI: 10.1029/2012JD017968.

Dottori, F., Kalas, M., Salamon, P., Bianchi, A., Alfieri, L., Feyen, L. 2017. An operational procedure for rapid flood risk assessment in Europe. *Nat. Hazards Earth Syst. Sci*. 17, 1111–1126. DOI:10.5194/nhess-17-1111-2017.

Emerton, R., Zsoter, E., Arnal, L., Cloke, H. L., Muraro, D., Prudhomme, C., Stephens, E. M., Salamon, P., Pappenberger, F.2018. Developing a global operational seasonal hydrometeorological forecasting system: GloFAS-Seasonal v1.0. *Geosci. Model Dev*. 11, 3327–3346. DOI: 10.5194/gmd-11-3327-2018.

Faergemann, H. 2012. Update on water scarcity and droughts indicator development (EEA – European Environmental Agency).

Farinosi, F., Giupponi, C., Reynaud, A., Ceccherini, G., CarmonaMoreno, C., De Roo, A., Gonzalez-Sanchez, D., Bidoglio, G. 2018. An innovative approach to the assessment of hydropolitical risk: A spatially explicit, data driven indicator of hydropolitical issues, *Global Environmental Change*, 52, 286–313. DOI: 10.1016/j.gloenvcha.2018.07.001.

Forzieri, G., Feyen, L., Rojas, R., et al. 2014. Ensemble projections of future streamflow droughts in Europe. *Hydrol. Earth Syst. Sci.* 18, 85–108. DOI: 10.5194/hess-18-85-2014.

Forzieri, G., Feyen, L., Russo, S., Vousdoukas, M., Alfieri, L., Outten, S., Migliavacca, M., Bianchi, A., Rojas, R., Cid, A. 2016. Multihazard assessment in Europe under climate change. *Clim Change* 137, 105–119. DOI: 10.1007/s10584-016-1661-x.

Gosling, S. N., Arnell, N. W. 2013. A global assessment of the impact of climate change on water scarcity. *Clim. Change* 1–15. DOI: 10.1007/s10584-013-0853-x

Haddeland, I., et al. 2014. Global water resources affected by human interventions and climate change. *Proc. Natl Acad. Sci.* USA 111, 3251–3256. DOI: 10.1073/pnas.1222475110

Hanasaki, N., et al. 2013. A global water scarcity assessment under shared socio-economic pathways: 2. Water availability and scarcity. *Hydrol. Earth Syst. Sci*. 17, 2393–413. DOI: 10.5194/hess-17-2393-2013

Hlásny, T., Trombik, J., Dobor, L., Barcza, Z., Barka, I. 2016. Future climate of the Carpathians. *Reg. Environ. Change* 16, 1495–1506. DOI: 10.1007/s10113-015-0890-2

ICPDR, 2013. ICPDR Strategy on Adaptation to Climate Change. 42 p.

ICPDR, 2015. The Danube River Basin District Management Plan. Part A-Basin-wide Overview. Update 2015. 164 p.

ICPDR, 2018. Danube River Basin Climate Change Adaptation. Revision and Update of the Danube Study. 115 p.

Jacob, D., et al. 2014. EURO-CORDEX: new high-resolution climate change projections for European impact research. *Reg. Environ.Change* 14, 563–578. DOI:10.1007/s10113-013-0499-2.

Jacobs-Crisioni, C., Diogo, V., Perpiña Castillo, C., Baranzelli, C., Batista e Silva, F., Rosina, K., Kavalov, B., Lavalle, C. 2017. TheLUISA Territorial Reference Scenario 2017: A technical description, Publications Office of the European Union, Luxembourg.

Karabulut, A., Egoh, B. N., Lanzanova, D., Grizzetti, B., Bidoglio, G., Pagliero, L., Bouraoui, F., Aloe, A., Reynaud, A., Meas, J., Vandecasteele, I., Mubarek, S. 2016. Mapping water provisioning services to support the ecosystem-water-food-energy nexus in the Danube River Basin. *Ecosyst. Serv*. 17, 278–292. DOI: 10.1016/j.ecoser.2015.08.002

Kiguchi, M., Shen, Y., Kanae, S., Oki, T. 2015. Reevaluation of future water stress due to socio-economic and climate factors under a warming climate. *Hydrol. Sci. J*. 60, 14–29. DOI: 10.1080/02626667.2014.888067

Laaha, G., Parajka, J., Viglione, A., Koffler, D., Haslinger, K., Schöner, W., Zehetgruber, J., et al. 2016. A three-pillar approach to assessing climate impacts on low flows. *Hydrology and Earth System Sciences* 20, 3967. DOI: 10.5194/hess-20-3967-2016

Lavalle, C., Baranzelli, C., Batista e Silva, F., Mubareka, S., Rocha Gomes, C., Koomen, E., Hilferink, M. 2011. A high resolution land use/cover modelling framework for Europe. In: ICCSA 2011, Part I, LNCS 6782, 60–75.

Lehner, B., Döll, P., Alcamo, J., Henrichs, T., Kaspar, F. 2006. Estimating the Impact of Global Change on Flood and Drought Risks in Europe: A Continental, Integrated Analysis. *Climatic Change* 75, 273–299, DOI:10.1007/s10584-006-6338-4.

Malagó, A., Bouraoui, F., Vigiak, O., Grizetti, B., Pastori, M. 2017 Modelling water and nutrient fluxes in the Danube River Basin. *Science of The Total Environment* 603–604, 196–218. DOI: 10.1016/j.scitotenv.2017.05.242

Moss, R., et al. 2010. The next generation of scenarios for climate change research and assessment, *Nature* 463, 747–756. DOI: 10.1038/nature08823

Mubareka, S., Maes, J., Lavalle, C., De Roo, A. 2013. Estimation of water requirements by livestock in Europe. *Ecosyst. Serv.* 4, 139–145. DOI: 10.1016/j.ecoser.2013.03.001

Pieczka, I., Pongrácz, R., Bartholy, J. 2011. Comparison of Simulated Trends of Regional Climate Change in the Carpathian Basin for the 21st Century Using Three Different Emission Scenarios. *Acta Silvatica et Lignaria Hungarica* 7, 9–22.

Prudhomme, C., et al. 2014. Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment. *Proc. Natl Acad. Sci.* USA 111, 3262–3267. DOI: 10.1073/pnas.1222473110

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N., Rafai, P. 2011. RCP 8.5—A scenario of comparatively high greenhouse gas emissions. *Climatic Change* 109, 33–57, DOI:10.1007/s10584-011-0149-y.

Schewe, J., et al. 2014. Multimodel assessment of water scarcity under climate change *Proc. Natl Acad. Sci.* USA 111, 3245–3250. DOI: 10.1073/pnas.1222460110

Schlosser, C. A., Strzepek, K., Gao, X., Fant, C., Blanc, E., Paltsev, S., Jacoby, H., Reily, J. 2014. The future of global water stress: an integrated assessment. *Earth's Future* 2, 341–361. DOI: 10.1002/2014ef000238

Sperna Weiland, F. C., van Beek, L. P. H., Kwadijk, J. C. J., Bierkens, M. F. P. 2012. Global patterns of change in discharge regimes for 2100. *Hydrol. Earth Syst. Sci*. 16, 1047–1062. DOI:10.5194/hess-16-1047-2012.

Stagl, J.C., Hattermann, F.F. 2015. Impacts of climate change on the hydrological regime of the Danube River and its tributaries using an ensemble of climate scenarios. *Water* 7, 6139–6172. DOI: 10.3390/w7116139

Stahl, K. 2001. Hydrological Drought – a Study across Europe, PhD thesis, Freiburger Schriften zur hydrologie (No. 15), Institut fur Hydrologies, Universitat Freiburg, Freiburg.

Thiemig, V., Bisselink, B., Pappenberger, F., Thielen, J. 2015. A panAfrican medium-range ensemble flood forecast system. *Hydrol. Earth Syst. Sci.* 19, 3365–3385. DOI: 10.5194/hess-19-3365-2015.

Vandecasteele, I., Bianchi, A., Batista e Silva, F., Lavalle, C., Batelaan, O. 2014. Mapping current and future European public water withdrawals and consumption. *Hydrol. Earth Syst. Sci*. 18, 407–416. DOI:10.5194/hess-18-407-2014.

van der Knijff J.M., Younis, J., De Roo, A.P.J. 2010. LISFLOOD: A GIS-based distributed model for river-basin scale water balance and flood simulation, *International Journal of Geographical Information Science* 24(2), 189–212. DOI: 10.1080/13658810802549154

van Vliet, M. T. H., Franssen, W. H. P., Yearsley, J. R., Ludwig, F., Haddeland, I., Lettenmaier, D. P., Kabat, P. 2013. Global river discharge and water temperature under climate change. *Glob. Environ. Change* 23, 450–464. DOI: 10.1016/j.gloenvcha.2012.11.002

Vörösmarty, C. J., Green, P., Salisbury, J., Lammers, R. B. 2000. Global Water Resources: Vulnerability from Climate Change and Population Growth. *Science* 289, 284–288, DOI:10.1126/science.289.5477.284.

Wada, Y., Gleeson, T., Esnault, L. 2014. Wedge approach to water stress. Nat. Geosci. 7, 615–617. DOI: 10.1038/ngeo224