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Freshwater availability

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Main messages

- According to the combined SSP2–RCP4.5 scenario, water demand will continue to rise globally, between 2010 and 2050. In many regions, the largest projected increase is in irrigation water demand to ensure food production for a growing population, particularly in the MENA region (the Middle East and northern Africa) and in Southeast Asia and China. The projected increase in water demand from other sectors (industry, households), in these regions, is less marked as it is mitigated by improved efficiency.
- This scenario also projects an increase in water demand for Sub-Saharan Africa, the largest relative rise compared with that in the rest of the world. Here, the projected efficiency does not improve, leading to a substantial rise in domestic water demand in addition to that for irrigated food production. This future development is particularly strong over Equatorial Africa.
- The projected global rise in water demand puts more strain on water resources. According to the projections, this will increasingly lead to the use of non-renewable or transboundary water resources. The exploitation of non-renewable groundwater resources is heaviest in dryland areas but not exclusively so; substantial increases are also projected for Indonesia and Mexico.
- In some parts of the world, the use of non-renewable groundwater due to the socio-economic developments under the SSP2 scenario is somewhat alleviated by the projected increase in groundwater recharge as a result of climate change, particularly across the monsoon belt that extends from Africa to East Asia. Climate change projections show a negative impact on water availability in temperate and Mediterranean regions, most notably in Europe.
- As a result, water scarcity increases, worldwide, under the combined SSP2–RCP4.5 scenario. Most heavily affected are the MENA region, Central Asia and India, where, without the means to combat water scarcity, it can be economically and socially debilitating. Also, water scarcity is on the rise in some major agricultural areas, including the High Plains in the United States and areas in Canada, Argentina, Australia, and north-eastern China. Here, the viability of agricultural production becomes limited through groundwater exploitation.

1.1.1 Introduction

Globally, freshwater resources are increasingly affected by climate change and taxed by human water demand as a result of population growth and improving living standards. An intrinsic part of these socio-economic changes are shifts in land use, including a growth in irrigated area to secure crop yields in the more arid regions of the world. Yet, these changes in environmental factors interact with the global water cycle. This, in turn, leads to shifts in both water use and water availability. In time, this jeopardises water and food security, and threatens biodiversity and supporting ecosystems. Among other things, this concerns:

- Reduced moisture availability as climate change affects rainfall patterns, which interacts with land-cover change and may reduce agricultural yields and increase the demand for irrigation water;
- The availability of renewable water resources, as determined by the amount of run-off and groundwater recharge;
- Uncertainty about the degree to which non-renewable groundwater resources will remain available under increased withdrawals.

Definitions

This document explores the current (i.e. for 2010) distribution of water security, in space and time, around the world and the expected changes as a result of projected shifts in socio-economic and climatic factors (by 2050).

Water scarcity, here, is defined as *the lack of sufficient available water resources to meet the demand* within a region. Hence, water scarcity is a relative measure, as it depends on availability and demand and this demand may vary with the local standard of living. This sets it apart from water stress, which is the *inability of the available water resources to meet a pre-defined, absolute demand*. A comparison of these metrics is provided in Table 2.

Water resources *are reserves of accessible and usable water* and these may be renewable—meaning that they replenish themselves on a human timescale—or non-renewable. If exploitation, on average, does not exceed the rate of replenishment, water use is considered to be environmentally sustainable. Exploitable water resources typically concern *blue water* or *water in liquid form that can be pumped, piped, and priced*.

Green water is *rainwater that is stored in the soil and transpired by plants* (Falkenmark, 1997) and that sustains net primary production (including crop growth). This water resource is valuable but cannot be actively extracted and is therefore generally excluded from assessments of water scarcity (see Wada and Bierkens, 2014, for an exception) and often expressed in terms of the yield gap due to water shortages (e.g., Jägermeyr et al., 2016).

Water demand *is the desired amount of water to sustain human lives and livelihoods* and can be subdivided over various sectors, which conventionally include households, industry, electricity production, and agriculture (including livestock and irrigation). Water demand is further split into gross and net water demand; the former corresponds to the total amount of water that is taken out of the hydrological system and is needed throughout the process, whereas the latter denotes the net quantity that is taken from the hydrological system and that is stored in the product or eventually evaporates.

Withdrawal or abstraction are terms used to denote the total amount of water taken out of the system, which is equivalent to gross demand (at unlimited availability), whereas consumption is the amount that is used, equivalent to net demand. The difference between the amounts withdrawn and consumed is the return flow, which may become contaminated in the process and is sometimes called *grey water* to indicate that this water, if left untreated, although not physically lost, may not be suitable for further use at the point of discharge or further downstream (Mekkonen and Hoekstra, 2011). The difference between demand and withdrawal is the water gap, and, dependent on the process, this may lead to more or less direct costs and indirect losses. A water gap may arise when an insufficient amount of water or water of insufficient quality is available (*physical water scarcity*) or the infrastructure to deliver water where it is needed is lacking or failing (*economical water scarcity*). This analysis concerns physical water scarcity only.

Trends so far

Rapid population growth and socio-economic developments, and the impact of human activities on the hydrological system, either directly or via anthropogenic climate change, have led to concerns about long-term sustainability and safe operating space for human water use (e.g. Gleick, 1998; Röckström et al., 2009; Vörösmarty et al., 2010). Assessments indicate that, in the second half of the 20th century, the share of the global population experiencing water scarcity increased from 27% to 43% (Wada et al., 2011).
The global population is projected to increase to 9 billion in 2050 (Table 3). At the same time, climate change will lead to higher global temperatures, increasing evaporation over land and the oceans, larger amounts of precipitation, greater intra- and inter-annual variability, and shifts and changes in atmospheric circulation. This intensification of the hydrological cycle will negatively affect water availability. At the same time, water demand may increase, as more 'blue' water is needed to secure the water and food supply for the growing population and to maintain current production levels in agriculture, industry and energy.
To investigate how water scarcity is impacted by the projected changes, several hydrological impact studies have been undertaken, often combining different global hydrological models. Examples are the climate projections of the ISI–MIP project (e.g. Schewe et al., 2014) and the WFaS initiative (Wada et al., 2016). For the period up to 2050, these studies show an increase in water scarcity, particularly in regions where large population increases coincide with limited water resources (the Middle East and northern Africa, and South Asia), but also in regions where water availability will become variable under a more erratic climate (Europe, Midwestern United States and the Pacific coast of North America, Argentina, and Australia). This study builds on and adds to these earlier studies by using a consistent scenario of projected land cover, water demand, and climate (drawing from SSP2 and RCP4.5) to evaluate hydrological changes across the globe, at a ~10 km resolution, from the global hydrological model PCR–GLOBWB. On the basis of these results, water scarcity is quantified and evaluated in terms of changes in water availability and demand, the long-term sustainability of water use, and the impact on the socio-economic development.

Water scarcity *directly* relates to the following Sustainable Development Goals:

- SDG 1. No poverty. Too little water limits food production and has a negative impact on the economy—unless countries (e.g. Gulf States) are wealthy enough to import food and products and, for those with access to large bodies of salt water, to make their own drinking water through desalination.
- SDG 2. Zero hunger. Water scarcity limits crop yields, affects food supply, and leads to hunger, in cases where countries strongly rely on their own food production and are not wealthy enough to import sufficient amounts of food on the global market.
- SDG 3. Good health and well-being. A lack of sufficient water resources, generally, leads to relatively high levels of pollution of the water that is available, with diseases spreading more easily as a result.
- SDG 6. Clean water and sanitation. Similar to the relationship with SDG 3 (see above).
- SDG 13. Climate action. Climate change is an important driver of increasing water scarcity. Problems may become aggravated in regions that are already water stressed, and regions currently not affected may, in the future, suffer from lower water availability.

Water scarcity also relates to a number of Sustainable Development Goals in an *indirect* way:

- SDG 8. Decent work and economic growth. Sufficient clean freshwater resources are the basis for all economic processes.
- SDG 11. Sustainable cities and communities. Not having access to sufficient freshwater resources makes it difficult for cities to be sustainable. In addition, cities without access to sufficient freshwater resources have an even stronger need to be sustainable—in particular, when overexploitation of groundwater reserves affects the sustainability of the living environment.

- SDG 15: Life on land. In water-scarce places, local populations use most of the water resources, leaving little water to support biodiversity. In addition, biodiversity also suffers from overexploitation of groundwater reserves.
- SDG 16. Peace, justice, and strong institutions. Water scarcity may lead to conflict, due to its impact on poverty, hunger, and migration, and because downstream regions depend on upstream regions. Moreover, a large number of the water-stressed regions of the world also suffer from weak governance (exceptions do exist, such as in Israel and Jordan).

1.1.2 Goal

Freshwater availability is threatened by a multitude of risks. This document investigates the impact of environmental change on global freshwater availability in relation to changing human demand, and identifies current and emerging hotspots of water scarcity. To this end, simulations by a state-of-the-art global hydrological model were used to compare the situation in 2050 with the reference situation in 2010. In particular, the following research objectives were covered:

- To assess changes in the availability of renewable water resources (surface water, groundwater);
- To determine changes in water demand and water consumption, for various sectors (irrigation, livestock, industry, and households);
- To investigate the effect on per-capita water availability, the so-called *water capital*, and highlight the origins of the water used and its attribution to the aforementioned sectors;
- This information, subsequently, is to be used to determine the dependence on non-renewable water resources or external, transboundary water resources, thus indicating where freshwater availability is under threat.

As water use implies the presence of infrastructure and some level of governance, assessments were made for administrative units that reflect such organisation, ranging from water provinces (i.e., parts of a country or province within the same river basin) to entire countries and socio-economic agglomerations (IMAGE regions).[1] This study only looks into aspects of physical water scarcity. Water quality (see also the document on health, nutrients and water quality) is not addressed, here, and would come on top of the effects evaluated here.

1.1.3 Methods and analysis

1.1.3.1 Scenario modelling

Simulations were carried out with the global hydrological model PCR–GLOBWB (Van Beek et al., 2011; Sutanudjaja et al., 2018), which is raster-based and was applied here at 5’ (~9 km at the equator). In addition to a detailed representation of the terrestrial part of the hydrological cycle, PCR–GLOBWB includes a module to evaluate water demand in light of the available freshwater resources (Figure 1). Surface water resources comprise rivers, lakes and reservoirs. Rivers propagate the accumulated run-off as discharge, and inertia and frictional resistance are considered to propagate flows realistically along the channel. Lakes and reservoirs interrupt the river network and buffer and modify the discharge by their size, either naturally in the case of lakes or intentionally on the basis of a set of operational rules in the case of reservoirs. Groundwater resources comprise both renewable and non-renewable groundwater reserves. The amount of desalinated water is added to these water resources.
Demand from industry, households and livestock farming are also enforced in PCR–GLOBWB, in terms of monthly gross and net demand. The demand for irrigation water, however, is computed dynamically on the basis of meteorological conditions and soil moisture availability, and is further increased to also take additional losses into account, caused during transport and application (irrigation efficiency). Gross demand from all sectors represents the amount of water that can be extracted from the system in light of

[1] As none of these administrative units is per definition hydrologically sound, their topology and influence on inflow and outflow should be considered carefully to ensure that the water balance remains closed.

the actual availability. With respect to irrigation water, any water that is not lost during evapotranspiration may enhance groundwater recharges. In industry, households, and livestock farming, an amount proportional to the net demand is consumed and the remainder flows back to the surface water system as return flow. Water quality is not explicitly considered by the model but partly included via lower return flows.

Although local water availability is confined to 5’, water demand may be met from water available in adjacent cells. . Here, blocks of 1 arc degree (~110 km) were considered, provided that all cells were adjacent and belonged to the same country. Over this area, a cell has access to water that comes from both renewable and non-renewable sources, including run-off, groundwater and desalinated water, and its demand is satisfied proportionally. Available river discharge is the actual flow from upstream neighbouring cells that results from all upstream hydrological processes, in which the amounts of water used in human consumption have been abstracted. In turn, the cell under consideration passes its actual discharge on to its downstream neighbour.

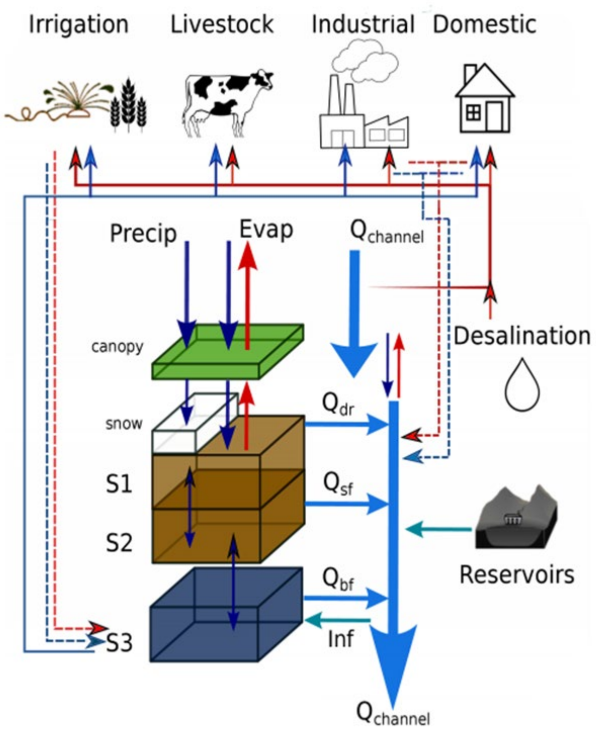


Figure 1. Model concept of PCR–GLOBWB. The left-hand side represents the vertical structure for the soil hydrology, including the canopy, soil column (stores 1 and 2), and the groundwater reservoir (store 3). Precipitation (*Precip.*) is in the form of rain when the air temperature (*T*) is above 0 °C and in the form of snow under lower temperatures. Snow accumulates on the surface, and melt is temperature driven. Potential evapotranspiration is broken down into canopy transpiration and bare soil evaporation, which are reduced to an actual rate (*Evap.*) on the basis of the moisture content of the soil. Vertical transport in the soil column arises from percolation or capillary rise (*P, blue arrows in soil column*). Drainage from the soil column to the drainage network occurs via direct run-off, interflow, or subsurface stormflow, and base flow (Q_{dr}, Q_{sf}, and Q_{bf}, respectively). Drainage accumulates as discharge ($Q_{channel}$) along the drainage network and is subject to a direct gain or loss depending on the precipitation and potential evaporation acting on the freshwater surface.

PCR–GLOBWB considers the entire global landmass with the exception of Greenland and Antarctica. For the reference period 1970–2010 the model is run with a daily time step and forced with a reconstruction of the historical climate over this period (monthly fields on precipitation, temperature, and potential reference evaporation from the CRU TS 3.23, downscaled to daily resolution on the basis of ERA20C). This simulation was initialised by running the simulation for the preceding 20 years and followed by simulations

that reflect various scenarios describing the combined effects of socio-economic change and climate change over the 21st century.
Future climate conditions were taken from the Representative Concentration Pathways scenarios (RCPs) that describe the evolution of four greenhouse gases (Van Vuuren et al., 2011). In this case, the RCP4.5 was used, in which emissions peak around 2040 with a concentration of 650 ppm and decline thereafter, resulting in an increased radiative forcing of 4.5 W/m^2 by 2100. For the corresponding changes in meteorological forcing (precipitation, temperature and potential reference evapotranspiration), the *delta method* was used. The historical data set for 1970–2010 was repeated to fill the 2011–2100 period and bias was corrected to conform to the normal period -the period over which climate statistics are calculated- , 1961–1990, so as to create a daily time series of realistic weather patterns. Climate change was based on the general circulation model (GCM) HadGEM2–ES (from CMIP5) and bias was corrected against WATCH in the ISI–MIP project (Hempel et al., 2013). For the various RCPs, the changes per month were determined relative to the normal period, 1961–1990. These changes, additive for temperature and multiplicative for precipitation and reference potential evaporation, were then smoothed using a 10-year central running mean, in order to limit the effect of interannual variability. This smoothed trend of monthly climate change was subsequently applied to the extended historical weather pattern, in order to obtain a daily time series that reflects the projected climate change over the 2011–2060 period, preserving a variability comparable to that of the historical period and is not too heavily biased by model errors and uncertainty that characterise GCM results.

To set the socio-economic conditions for the historical period and future scenarios, we relied on a large number of data sets from which information was converted into the required model parameterisation with a spatial resolution of 5'. Further local detail was preserved by including sub-grid variability. For the future, projected changes over the 2011–2060 period were taken from the SSP scenarios (Shared Socio-Economic Pathways) that describe trends in the development of society and the environment in the 21st century, on regional and global scales (for details, see the document on these scenarios). Here, the Middle-of-the-Road scenario (SSP2) was used, in which the total global population is projected to increase by 1 to 3 billion people, reaching about 9 billion by 2050. The economic growth in SSP2 follows historical trends.

Information on land-cover conditions and crop types was taken from the IMAGE model and blended with existing information on crop calendars and natural vegetation types. Seven land-cover classes were thus created, consisting of two natural classes (short and tall natural vegetation) and five on agricultural land cover (urban, rainfed cultivation, irrigated cultivation of paddy crops, irrigated cultivation of non-paddy crops, and pasture/rangeland). For the irrigated land-cover classes, a certain level of irrigation water efficiency was set (see also the document on *Water, climate and food production*). Information on increases in non-irrigation water demand and irrigated area expansion was also used to project groundwater pumping capacity, on the basis of historical observations. However, for the period after 2010, desalination levels and reservoir capacity were kept at the level of 2010, due to a lack of data.

1.1.3.2 Analysis

<u>Temporal and spatial aggregation</u>
Most findings are evaluated by comparing two benchmark years (2010 and 2050) that both cover a 10-year averaging interval to reduce the influence of anomalous climate conditions on the results (i.e. 2001–2010 and 2046–2055, respectively).
Spatial aggregation was carried out at the level of administrative units (i.e. water provinces (Straatsma et al., 2013[2]), countries, or IMAGE regions). In total, 26 IMAGE regions were identified and subsequently grouped into 10 larger regions to ease comparison (Table 1). In order to preserve their shape and size in detail, spatial processing was carried out at 5'. Administrative units do not coincide with the drainage network, meaning that water fluxes, particularly river discharges[3], can cross their boundaries multiple times and thus complicate any subsequent analysis of volumes. To overcome this problem, a topology was constructed from which the net riverine inflow and outflow could be derived.

[2] http://w2i.geo.uu.nl/
[3] Lateral groundwater flow is much slower and thus considered only in the vertical in PCR–GLOBWB.

Metrics
In the literature, different metrics (see Wada et al., 2011 for an overview) are used to express water scarcity; for example, on the basis of reported statistics or model results, such as those simulated here with PCR–GLOBWB. Generally, these metrics are indices that relate availability to requirement (i.e. water demand). Often, long-term environmental constraints are incorporated in the availability, to explore the limits of sustainable development. Most indices are ratio-based, to allow for a qualitative comparison. However, this limits their usefulness for scenario studies, as both numerator and denominator may change.

In order to overcome this inherent shortcoming of indices, all comparisons here are first based on absolute quantities or the changes therein. To compute changes, results were then aggregated over the 10-year periods, with a focus on 2010 and 2050, and future conditions reflect the projected socio-economic and climatic changes taken from SSP2 and RCP4.5.

***Water gap index*: difference between gross water demand and water withdrawal**
At the coarsest level, developments are evaluated for the 10 regions defined in Table 1. Gross demand is contrasted against withdrawals to provide a critical assessment of water scarcity, for withdrawals are inherently limited by natural supply, infrastructure, and upstream water consumption. The difference between gross water demand and water withdrawal represents the unmet demand (*water gap*). These quantities can be evaluated as total per region or per capita. The latter accentuates the interaction between population growth and water scarcity; water demand may be limited by economic development and this, in turn, may be hampered by water scarcity. Thus, by expressing water availability and demand per capita, and by comparing them to estimates of desired water availability per capita (e.g. Falkenmark et al., 1997), a comprehensive image emerges of the so-called water capital, which is the potential of a region to exploit its water resources adequately and without negative impact on development.

Table 1. Amalgamation of the 26 IMAGE regions to 10 broader units. Note that Antarctica and Greenland are not part of the land mask of PCR–GLOBWB and consequently are not considered.

Region		*IMAGE Region (26)*	
1	Sub-Saharan Africa	8	Western Africa
		9	Eastern Africa
		10	Southern Africa
		26	Rest southern Africa
2	Middle East and northern Africa	7	Northern Africa
		17	Middle East
3	Western and Central Europe	11	Western Europe
		12	Central Europe
		13	Turkey
		14	Ukraine +
4	Russia and Central Asia	15	Asia-Stan
		16	Russia +
5	China and Koreas	19	Korea
		20	China +
6	South Asia	18	India +
7	Southeast Asia	21	Southeast Asia
		22	Indonesia +
8	Japan and Oceania	23	Japan
		24	Oceania
9	North America	1	Canada
		2	United States
10	Central and South America	3	Mexico
		4	Rest Central America
		5	Brazil
		6	Rest South America
Not considered		25	Greenland
		28	Antarctica

***Water Scarcity Index*: ratio of demand to availability of renewable water**

In order to highlight local differences within the regional analysis, three indices have been used to explore the strain water demand puts on the sustainable use of available water resources during 10-year periods centred on 2010 and 2050. The first is the Water Scarcity Index (WSI) that expresses demand as a dimensionless ratio of the availability of renewable water. For renewable water, river flow is used as it accounts for upstream human influences such as reservoir operation and consumption (cf. Wada et al., 2011). Demand represents net demand, i.e. the amount that is actually consumed and does not directly re-enter the hydrological cycle (e.g., Kundzewicz et al., 2007). From this net demand, any water that becomes available through desalinisation is directly subtracted, as it does not stem from the available freshwater resources. Values of the WSI are subdivided into different categories of real or potential water scarcity, where a value of 0.4 is used as a common threshold that can be compared to water availability per capita, as used by Falkenmark et al. (1997) (Table 2).

Table 2. Overview of water scarcity indicators (Falkenmark et al., 1997; Kundzewicz et al., 2007) used in the assessment of the water capital (from Wada, 2008).
The theoretical demand of 1,700 $m^3 \cdot capita^{-1} \cdot year^{-1}$ in Falkenmark et al. (1997) is roughly equivalent to the water withdrawal of 1,543 and 1,864 $m^3 \cdot capita^{-1} \cdot year^{-1}$, for the United States in 2010 and 2005, respectively (Source: FAO AQUASTAT).

Degrees of water stress	Per capita water availability ($m^3.capita^{-1}. year^{-1}$)	Water Scarcity Index WSI (-)	Definitions of degrees of water stress
No stress	> 1,700	WSI < 0.1	No water scarcity
Low stress	-	0.1 ≤ WSI < 0.2	Potential water scarcity
Moderate stress	1,700–1,000	0.2 ≤ WSI < 0.4	Looming water scarcity
High stress	1,000–500	0.4 ≤ WSI < 0.8	Experiencing water scarcity
Very high stress	< 500	WSI ≤ 0.8	Economic development is limited by water scarcity

The WSI is typically computed for data that have been aggregated over larger areas and longer periods than the original resolution of PCR–GLOBWB. The coarsest level of aggregation, here, concerns the IMAGE regions for which an annual time series was created to show the development of withdrawal per sector and its provenance from the available water resources. For the water provinces, a finer monthly time step is used to capture the effects of temporal variations in availability and demand. This temporal variability in WSI is weighted according to Wada et al. (2011) to yield the Dynamic Water Scarcity Index (DWSI) that accounts for differences in the persistence and recurrence of water stress. This index follows the same scale as the WSI (Table 2).

Two indices on the contribution of groundwater to the water supply
To evaluate the effect of reliability and sustainability, the contribution of groundwater to the water supply is evaluated by two indices. First, the fractional contribution of renewable and non-renewable groundwater withdrawals is computed relative to the total withdrawal. This fractional contribution has been computed at the finer level of the water provinces under the explicit assumption that these units coincide with or encompass the aquifers exploited.
Next, the groundwater footprint ratio (Gleeson et al., 2012) is used to evaluate sustainable limits to groundwater exploitation. The groundwater footprint ratio is the ratio between groundwater consumption and net recharge, where net recharge is the recharge minus the part from the base flow that should be reserved to meet the environmental flow conditions.
Here, total groundwater withdrawal is used as consumption, as some of the extracted water ends up in the surface water as return flow. Some of the irrigation water applied returns to the groundwater system and this is accounted for by using the actual recharge.
The groundwater footprint ratio signals if groundwater withdrawal is unsustainable when the ratio is greater than unity, indicating that more than once the actual surface area of the aquifer, A_A, is needed to fulfil its population's needs.

1.1.4 Results

1.1.4.1 Water demand and availability worldwide

Under the SSP2 scenario, the global population increases by 33%, from 6.8 billion in 2010 to 9.0 billion by 2050. Over that same period, and based on the simulation with PCR–GLOBWB as forced with RCP4.5, the gross water demand—the volume that, under ideal circumstances, is withdrawn from water resources—will increase, on average, by 24%, from 3,135 to 3,880 km^3 per year. Of this water, some will be returned to the streams, and the ensuing net demand—the amount of water that, under ideal circumstances, is consumed—increases by 41%, from 2,390 to 3,366 km^3 per year. Compared to the gross demand the relatively larger increase in net demand reflects the projected development that, by 2050, more people will consume more water while the water use becomes more efficient and return flows decrease. This trend of more efficient water use is also reflected in the irrigation water demand, which is projected to increase by a mere 17%, compared to a 37% increase in domestic water use (Table 3).

Table 3. Global annual run-off, population, and annual water demand, for 2010 and 2050, under the SSP2 scenario and RCP4.5. Values given are the mean over a 10-year period. Indexed values give the relative change by 2050 relative to the year 2010. In absence of scenario-specific information, livestock water demand and the supply of desalinated water were kept constant at the level of 2010. The relative contribution of the various sources to the withdrawal does not add up to a full 100%, due to rounding errors.

		Year		
		2010	2050	Indexed
Population	*Billions*	6.8	9.0	133%
Global run-off				
Total renewable	*km³·year-¹*	46,900	48,000	102%
Gross water demand	*km³·year⁻¹*			
Domestic		394	538	137%
Industry		885	1,178	133%
Livestock		16.6	16.6	100%
Irrigation		1,839	2,147	117%
Total		*3,135*	*3,880*	*124%*
Net water demand	*km³·year⁻¹*			
Total		*2,390*	*3,366*	*141%*
Water withdrawal				
Total	*km³·year⁻¹*	2,776	3,606	130%
Fraction of gross demand that is met		89%	93%	
Relative contribution				
Surface water		75%	76%	
Renewable groundwater		20%	19%	
Non-renewable groundwater		6%	5%	
Desalinated water		0.1%	0.1%	

On a global scale, availability of renewable water resources exceeds demand multiple times; annual global run-off is estimated at around 46,000 km^3 (see Wada et al., 2011, for an overview), and the gross demand only represents 8% of this total. However, it should be noted that water availability varies widely in both space and time. Irrigation water demand is proportionally high in dryland areas around the world—where renewable water resources are scarce—and the seasonal water demand is often out-of-phase with the supply. Droughts may further deteriorate this situation. Looking at global renewable water resources, the projected increase in global run-off is still larger than the increase in gross demand (1,100 vs 745 $km^3 \cdot year^{-1}$; Table 3). However, the increase in global run-off and water demand do not coincide spatially, and the sensitivity to water scarcity may increase on a region level. On average, though, a similar amount of the demand can still be met. In 2010, withdrawals were sufficient to meet 89% of the gross demand and this is projected to improve to 93% by 2050. This improved supply reflects the increased availability and, to a lesser extent, improved access to groundwater by 2050. The origin of these withdrawals remains virtually unchanged (Table 3), with surface water supplying around 75% of the total withdrawal, while 20% is taken from renewable groundwater and 5% from non-renewable groundwater. Desalination, kept constant in this study, supplies less than 0.1%, globally, although it is important on a regional level.

1.1.4.2 Water demand and availability on a regional scale: trends and hotspots

On a regional level, large differences are projected for population growth and related gross water demand (Figure 2). In terms of the largest absolute and relative increase, Sub-Saharan Africa stands out, with its population expected to double over 40 years, followed by South Asia, the Middle East and northern Africa (MENA). Growth will be close to the global average for Southeast Asia and the Americas, and negligible or declining for China and the Koreas, Japan and Oceania, Russia and Central Asia, and Europe.

An assessment of water demand, withdrawals, and availability, per capita, highlights global differences in water capital and helps explore effects that are obscured by a regional analysis based only on volume. When expressed per capita, gross water demand shows the actual water requirement and underlines the importance and developments per sector. Water withdrawal depends on availability, efficiency, and infrastructure—simulated in PCR–GLOBWB as functions of irrigation efficiency, reservoir capacity, desalination, and groundwater pumping capacity.[4] There are large regional differences in water demand per capita (Figure 3). The corresponding numbers of renewable water resources (total run-off) per region, in terms of totals and per capita, are specified per region in Table 4 and contrasted with the gross demand. Although, in many regions around the world, water availability per capita is much larger than gross demand per capita, it should be realised that water availability and demand may be distributed differently over space and time. Where the water demand is not being met, a water gap emerges, which negatively impacts water security and—if irrigation water demand is not met—food security. All in all, regional differences seem to become more pronounced, possibly with adverse effects on the sustainability and dependability of water resources, over time. Time series of the water demand and availability per IMAGE region are given in Figure 4.

Table 4. Regional development in total run-off, as a measure of renewable water resources, and gross demand for the years 2010 and 2050, under SSP2 and RCP4.5. Total run-off is shown in volume and per capita.

		2010			*2050*		
		Total Run-off		*Gross demand*	*Total Run-off*		*Gross demand*
Region		km^3	$m^3 \cdot cap^{-1} \cdot year^{-1}$	$m^3 \cdot cap^{-1} \cdot year^{-1}$	km^3	$m^3 \cdot cap^{-1} \cdot year^{-1}$	$m^3 \cdot cap^{-1} \cdot year^{-1}$
1	Sub-Saharan Africa	5,123	6,085.0	96	6,353	3,646.4	123
2	Middle East and northern Africa	110	298.9	415	167	282.7	332
3	Western and Central Europe	2,365	3,635.3	527	1,947	2,777.8	517
4	Russia and Central Asia	4,496	20,512.2	864	5,041	22,087.0	930
5	China and Koreas	2,475	1,724.7	430	2,507	1,849.2	520
6	South Asia	2,053	1,268.9	468	3,079	1,311.0	421
7	Southeast Asia	7,184	12,407.1	498	7,539	10,398.6	475
8	Japan and Oceania	1,451	9,962.2	792	1,466	10,130.6	687
9	North America	6,629	19,679.2	1,279	6,600	15,000.8	1,261
10	Central and South America	15,01	26,018.0	278	13,33	18,269.3	276

[4] Only groundwater pumping capacity and irrigation water efficiency change over time in SSP2, the former as a function of population and irrigated area, the latter on FAO projections. In the absence of data, reservoir capacity and desalinated water supply have been kept at 2010 levels.

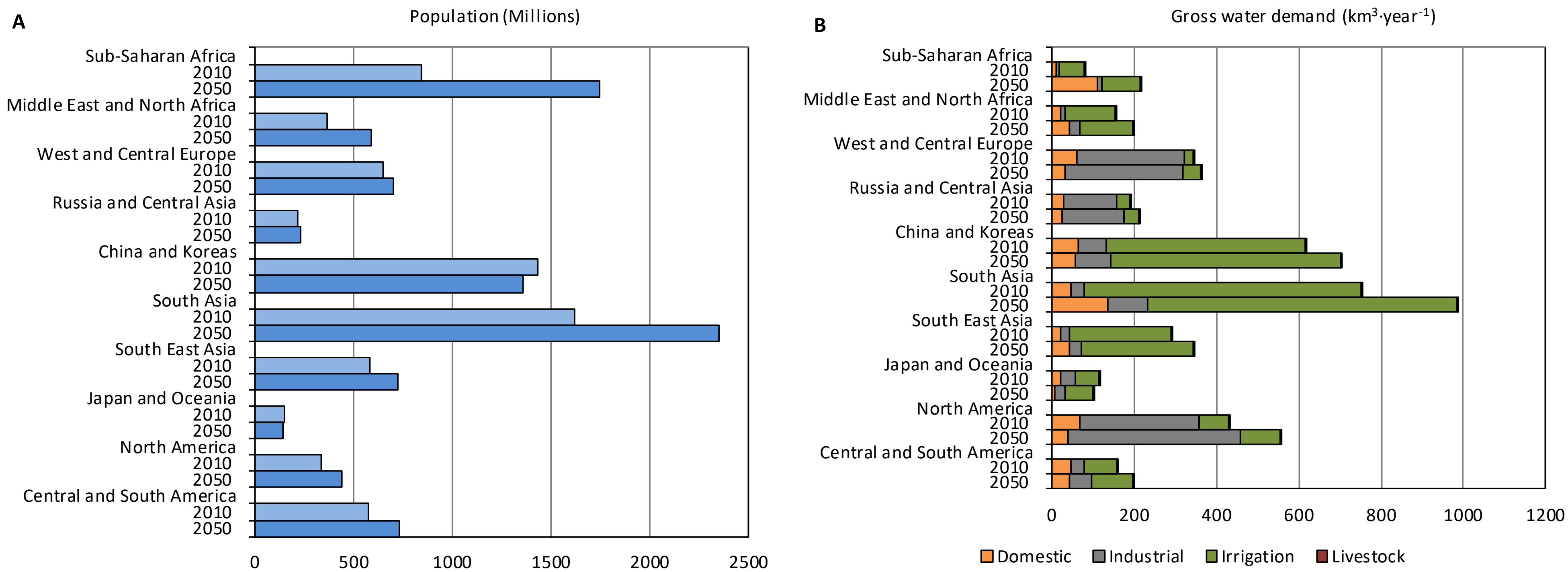


Figure 2. Regional developments for 2010 and 2050, under SSP2 with RCP4.5., for (a) population and (b) gross water demand

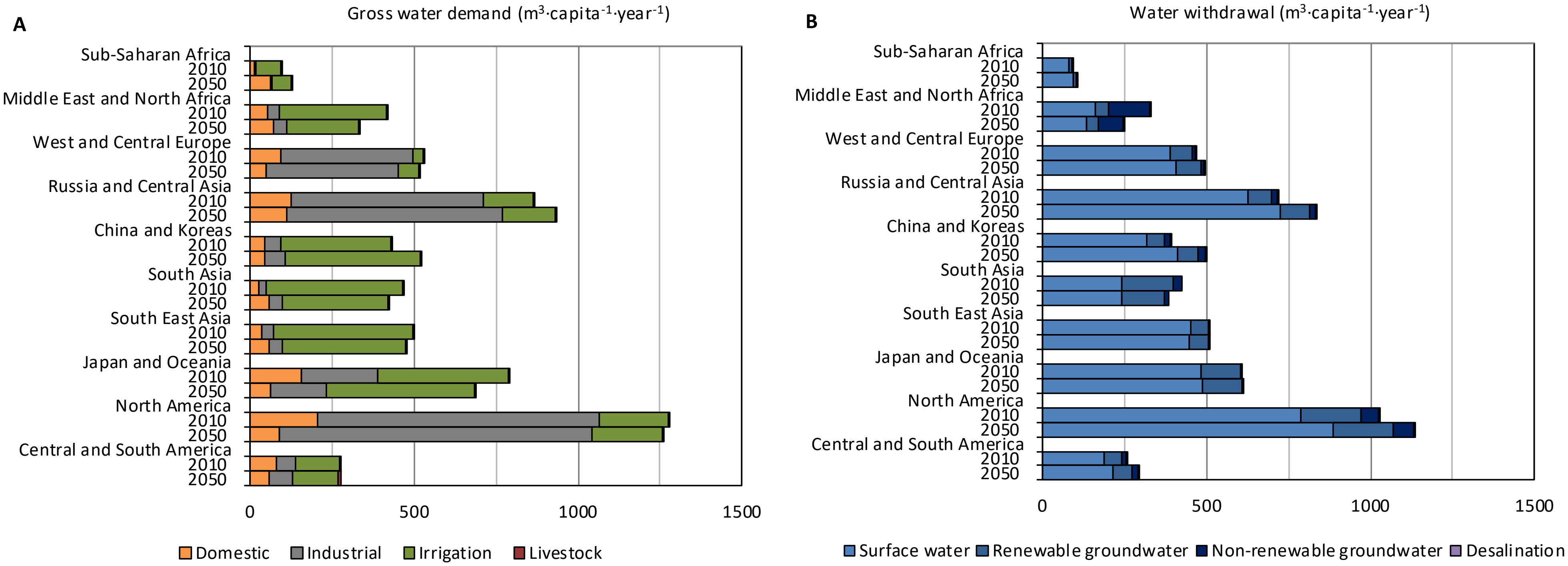
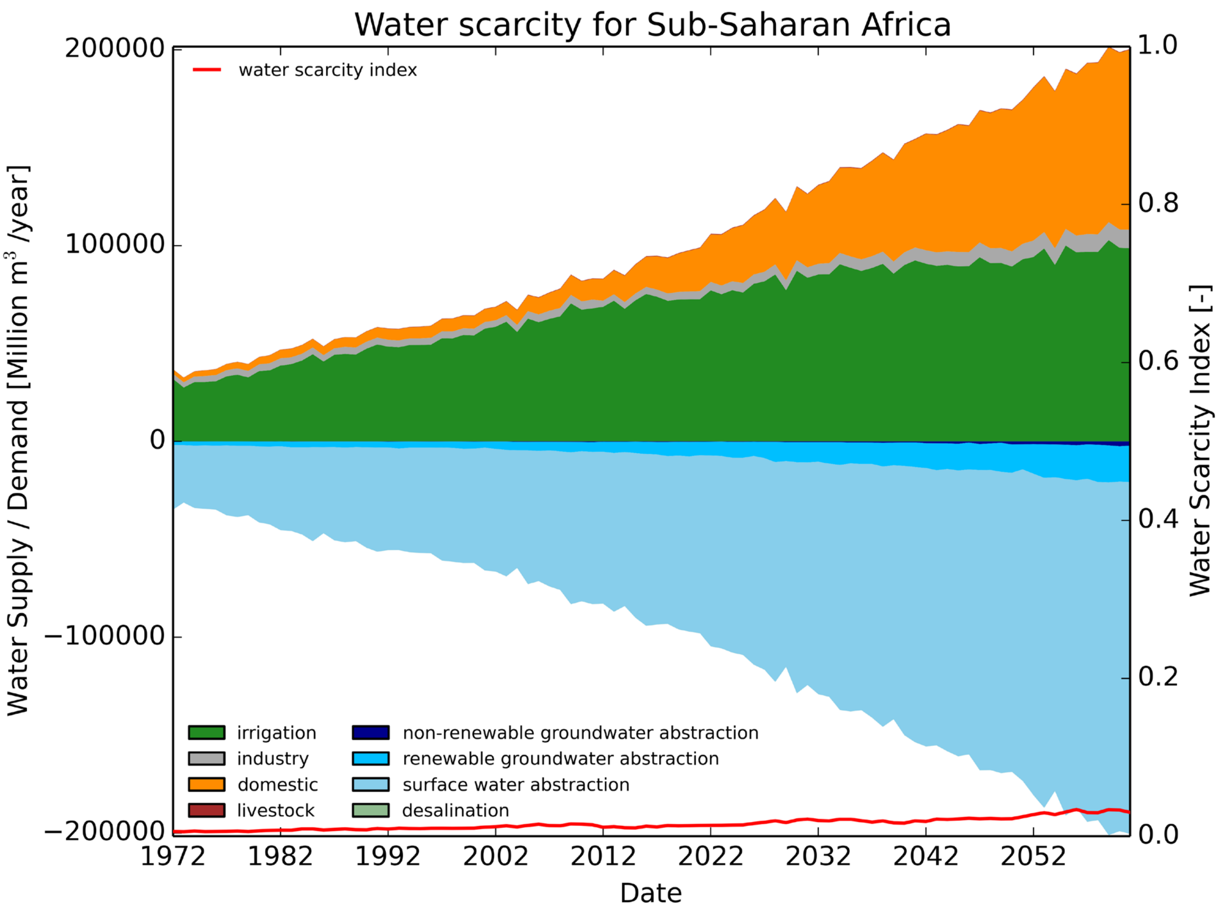


Figure 3. Regional developments in gross water demand and withdrawal per capita, for 2010 and 2050, under SSP2 with RCP4.5. The difference between demand (left bars, orange-grey-green-red) and withdrawal (right bars, different shades of blue) is the unmet demand or *water gap*.
Values given represent the mean over a 10-year period.


Water scarcity for Sub-Saharan Africa
water scarcity index
irrigation
industry
domestic
livestock
non-renewable groundwater abstraction
renewable groundwater abstraction
surface water abstraction
desalination
Water Supply / Demand [Million m³ /year]
Water Scarcity Index [-]
Date
200000
100000
0
−100000
−200000
1.0
0.8
0.6
0.4
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1972
1982
1992
2002
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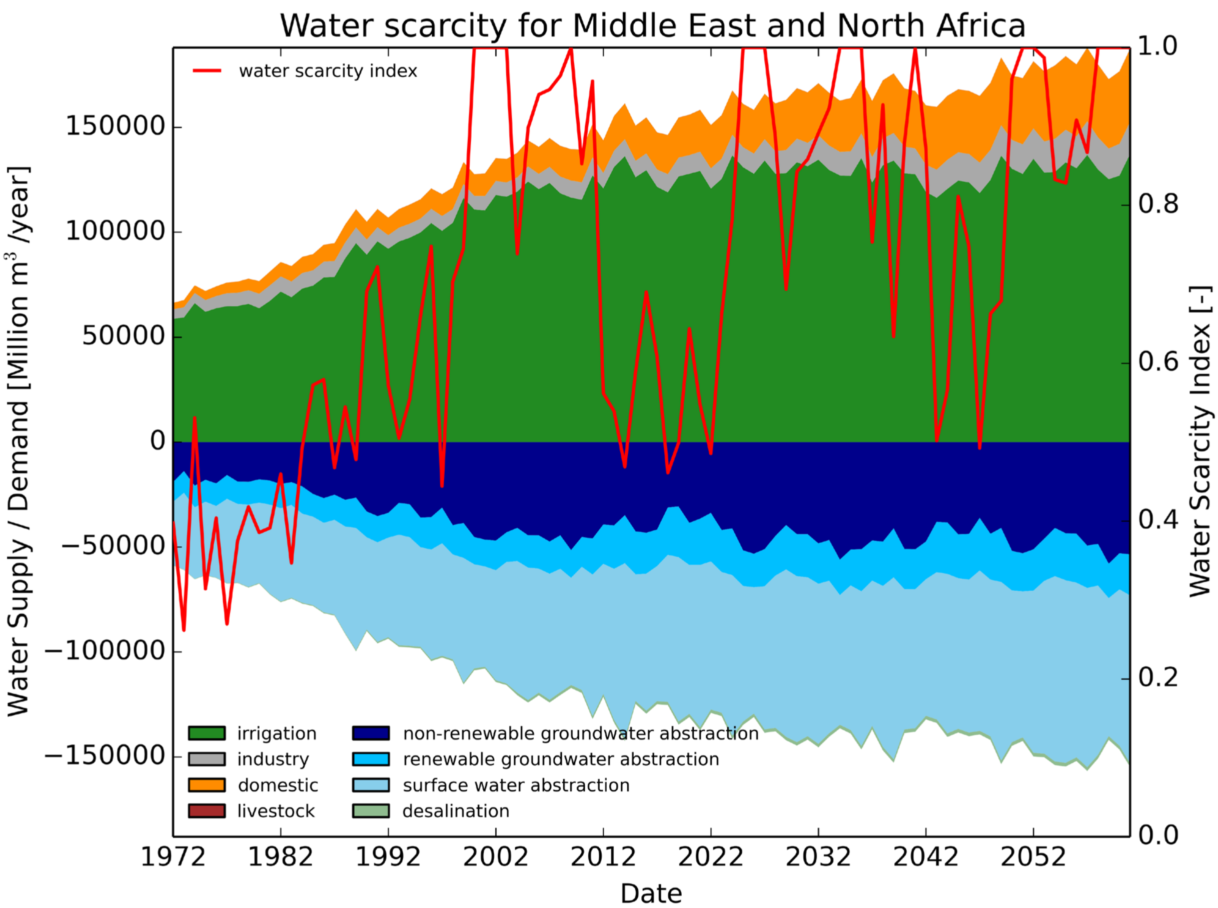
Water scarcity for Middle East and North Africa
water scarcity index
irrigation
industry
domestic
livestock
non-renewable groundwater abstraction
renewable groundwater abstraction
surface water abstraction
desalination
Water Supply / Demand [Million m³ /year]
Water Scarcity Index [-]
Date
150000
100000
50000
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−50000
−100000
−150000
1.0
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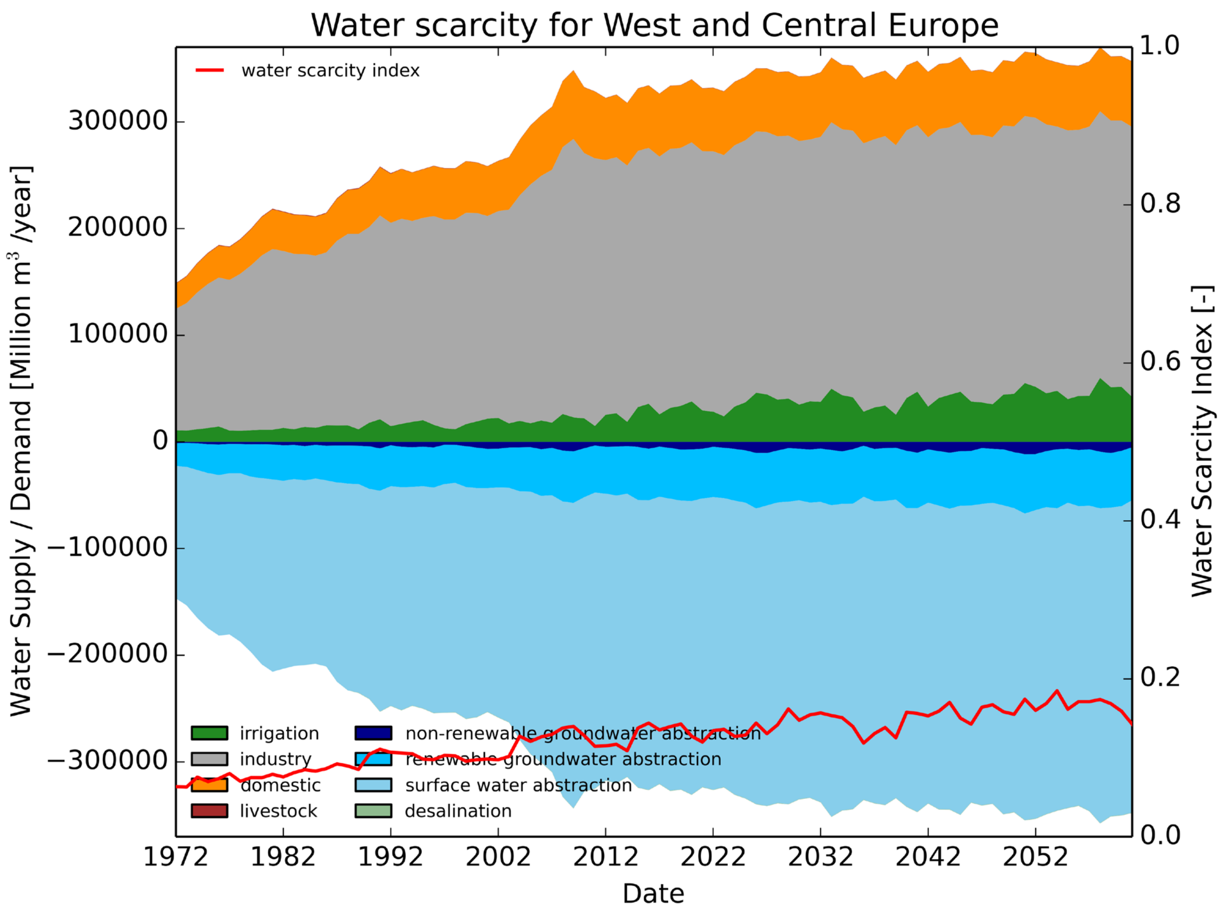
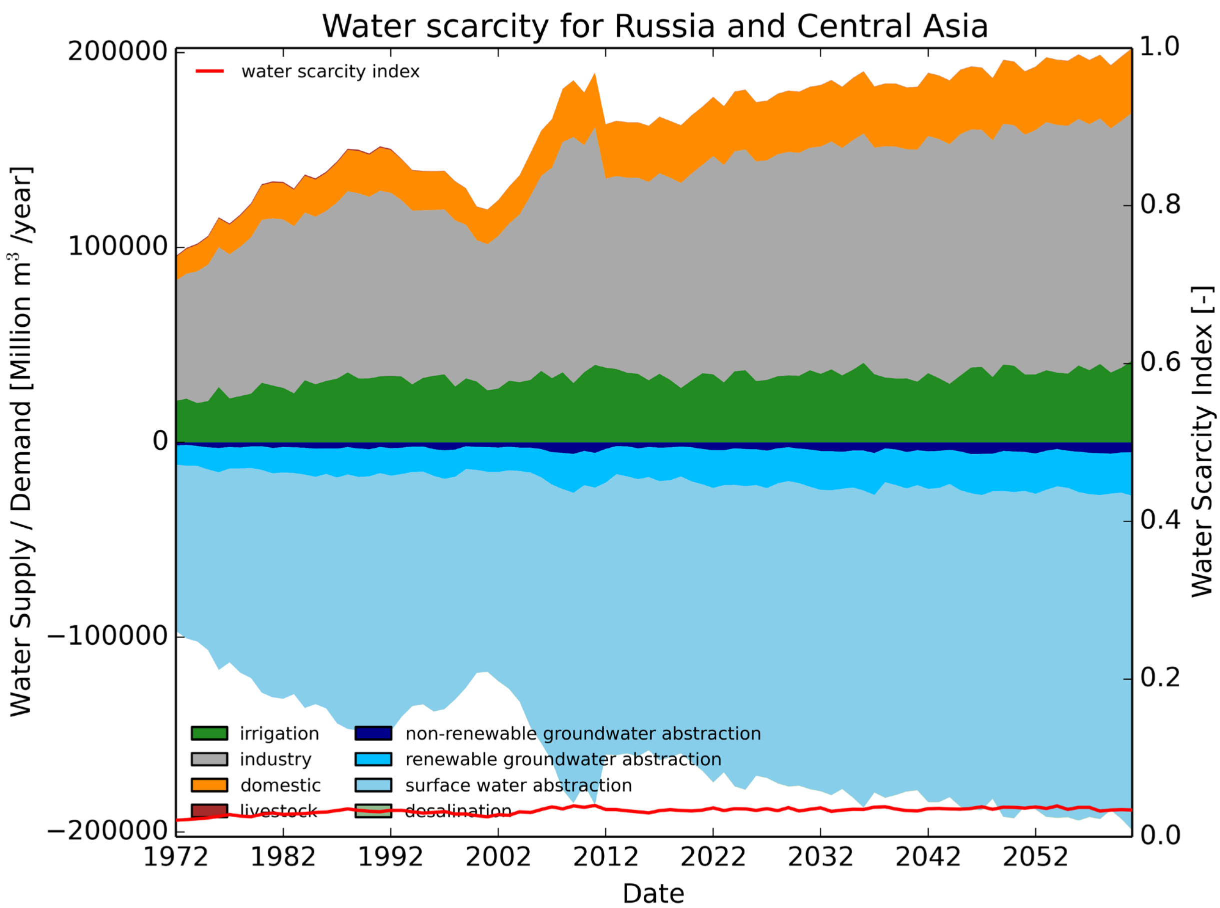
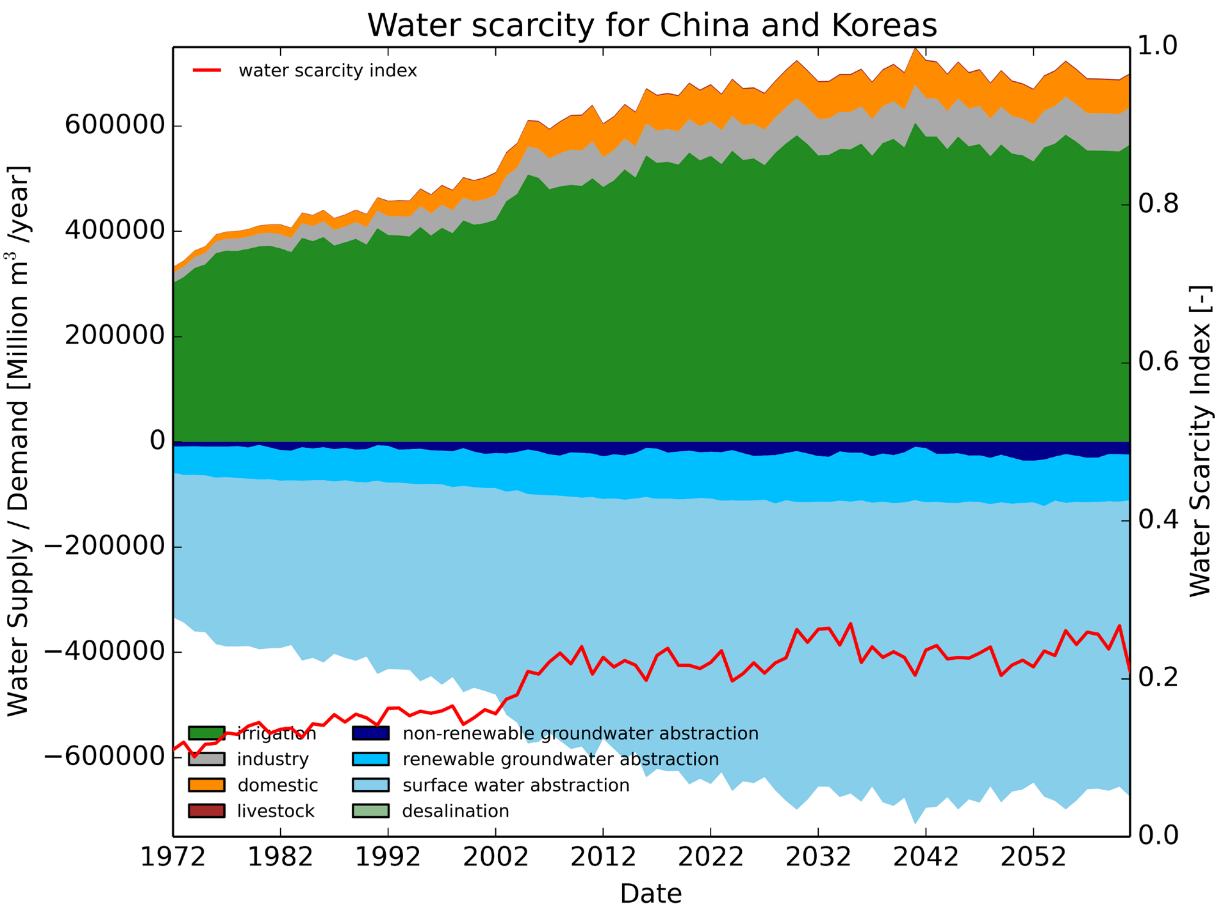

Water scarcity for West and Central Europe
water scarcity index
Water Supply / Demand [Million m^3 /year]
Water Scarcity Index [-]
Date
irrigation
industry
domestic
livestock
non-renewable groundwater abstraction
renewable groundwater abstraction
surface water abstraction
desalination


Water scarcity for Russia and Central Asia
water scarcity index
Water Supply / Demand [Million m^3 /year]
Water Scarcity Index [-]
Date
irrigation
industry
domestic
livestock
non-renewable groundwater abstraction
renewable groundwater abstraction
surface water abstraction
desalination



Water scarcity for China and Koreas
water scarcity index
Water Supply / Demand [Million m³ /year]
Water Scarcity Index [-]
600000
400000
200000
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−600000
1.0
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irrigation
industry
domestic
livestock
non-renewable groundwater abstraction
renewable groundwater abstraction
surface water abstraction
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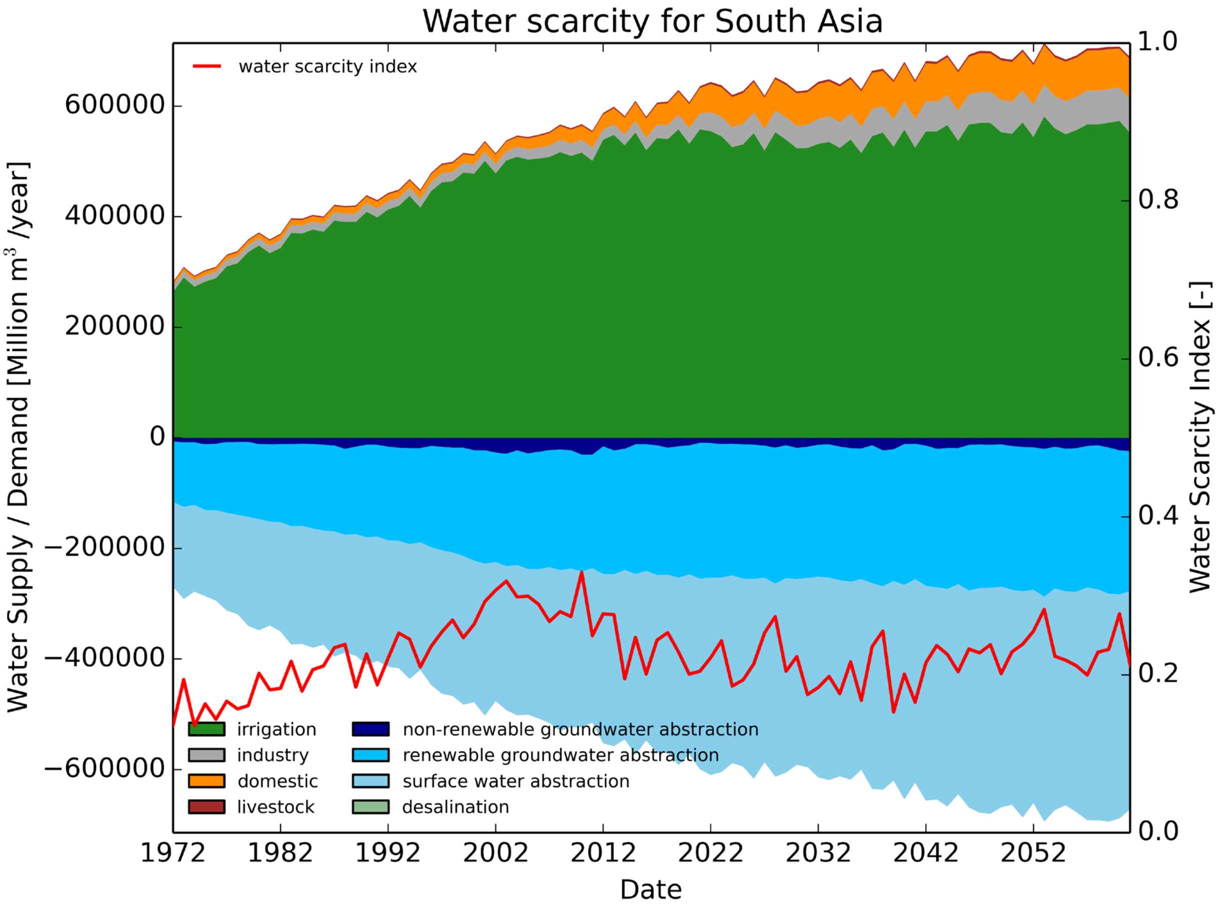

Water scarcity for South Asia
water scarcity index
Water Supply / Demand [Million m³ /year]
Water Scarcity Index [-]
600000
400000
200000
0
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−600000
1.0
0.8
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irrigation
industry
domestic
livestock
non-renewable groundwater abstraction
renewable groundwater abstraction
surface water abstraction
desalination
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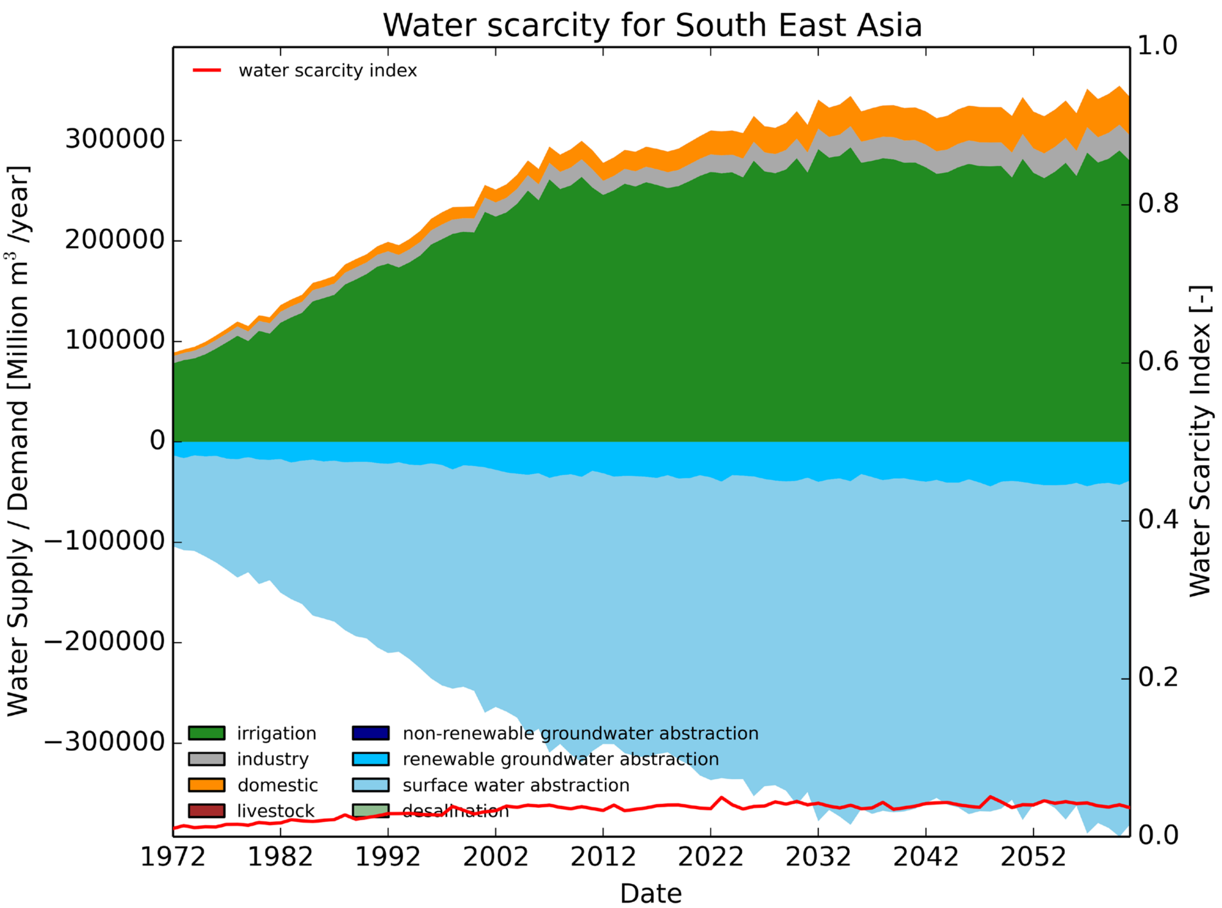
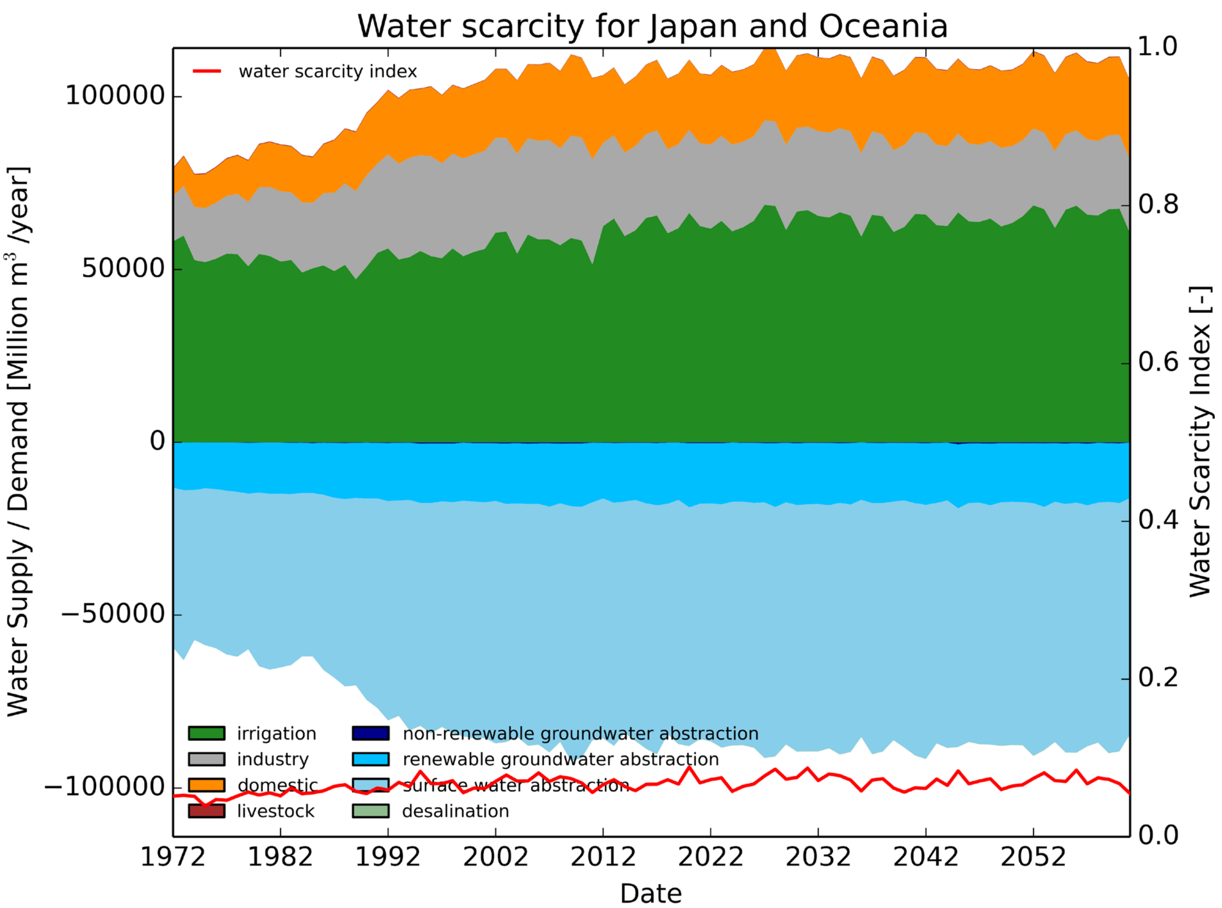
Date



Water scarcity for South East Asia
water scarcity index
300000
200000
100000
0
−100000
−200000
−300000
Water Supply / Demand [Million m³ /year]
1.0
0.8
0.6
0.4
0.2
0.0
Water Scarcity Index [-]
irrigation
industry
domestic
livestock
non-renewable groundwater abstraction
renewable groundwater abstraction
surface water abstraction
desalination
1972
1982
1992
2002
2012
2022
2032
2042
2052
Date



Water scarcity for Japan and Oceania
water scarcity index
100000
50000
0
−50000
−100000
Water Supply / Demand [Million m³ /year]
1.0
0.8
0.6
0.4
0.2
0.0
Water Scarcity Index [-]
irrigation
industry
domestic
livestock
non-renewable groundwater abstraction
renewable groundwater abstraction
surface water abstraction
desalination
1972
1982
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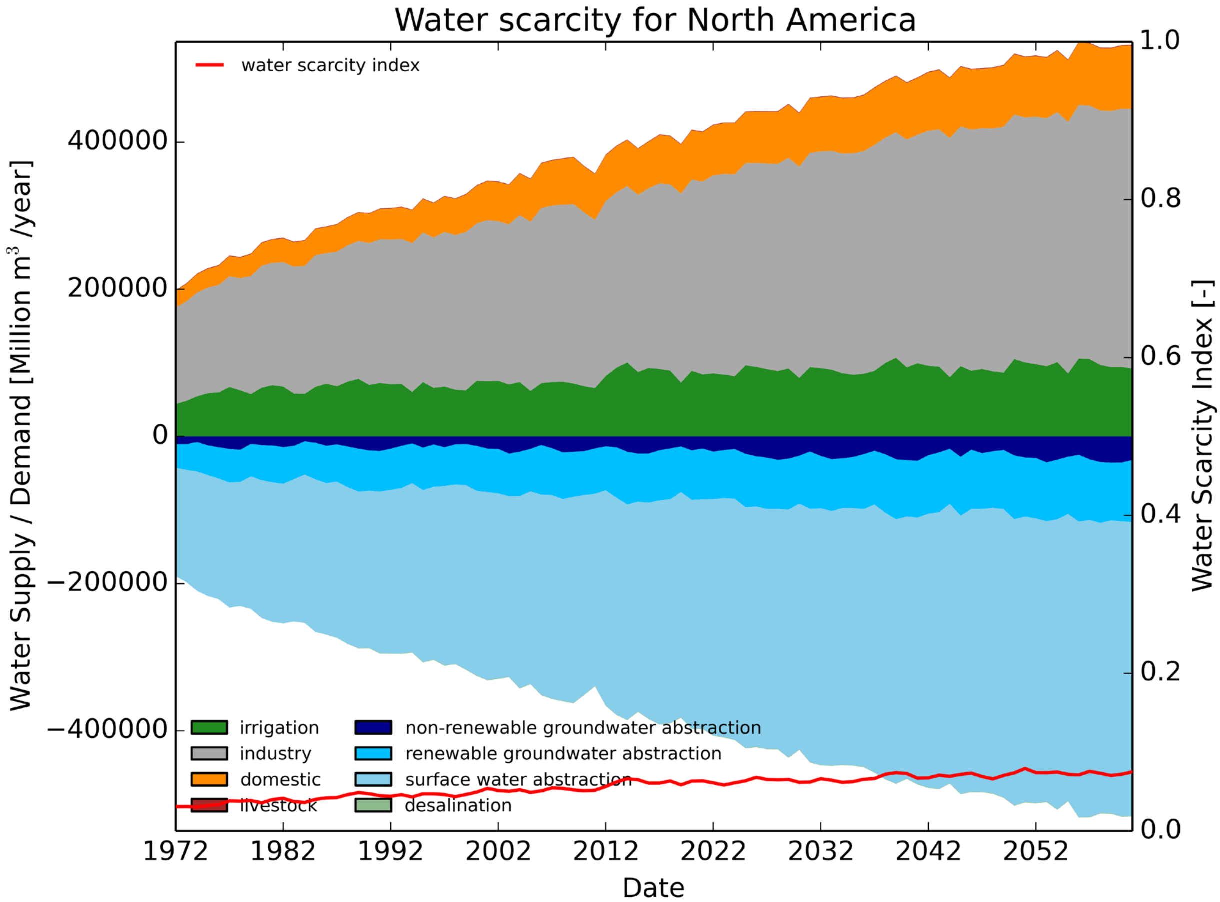
Date



Water scarcity for North America
water scarcity index
Water Supply / Demand [Million m³ /year]
400000
200000
0
−200000
−400000
Water Scarcity Index [-]
1.0
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irrigation
industry
domestic
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non-renewable groundwater abstraction
renewable groundwater abstraction
surface water abstraction
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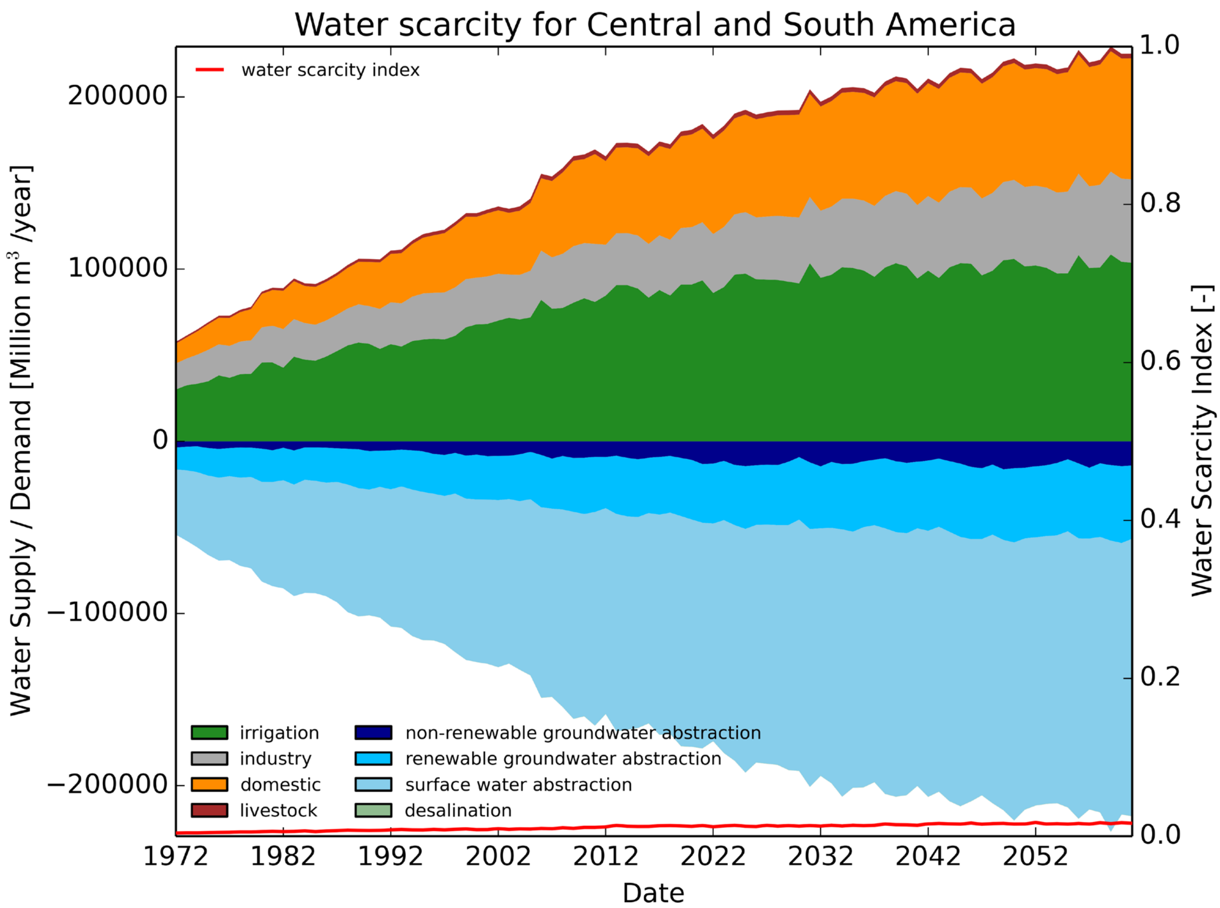

Figure 4. Annual withdrawals, supply, and scarcity per IMAGE region under SSP2 and RCP4.5. Time is plotted along the abscissa and each graph is subdivided into two panels, the top panel showing withdrawals per sector—domestic, industry, irrigation, and livestock—while the bottom panel shows withdrawals mirrored on an inverted scale per source—surface water, renewable (non-fossil) and non-renewable (fossil) groundwater, and desalination. In addition, the WSI (Table 2) is shown as a line plot, its range being constrained from zero to unity, and its axis plotted to the right of the plot area.

Here, the observed trends are described per region and evaluated further in terms of the aforementioned indices in order to identify hotspots.

Sub-Saharan Africa

- Regional analysis on volume (Figure 2):
  - Of all regions, Sub-Saharan Africa will experience the largest population growth (Figure 2a). Its population is projected to double over 40 years;
  - Also, compared with other regions, water demand will strongly increase between 2010 and 2050 (Figure 2b). Of all regions, the largest relative increase will occur in Sub-Saharan Africa, where demand is projected to increase by 167%, surpassing its increase in population (107%).
- Regional analysis per capita (Figure 3):
  - Water demand per capita, nevertheless, is and will remain the lowest of the entire world, with 123 m^3 per capita, per year, by 2050 (Figure 3; Table 4). This reflects the low levels of development and the absence of water infrastructure in large parts of the region.
    Domestic demand accounts for the largest increase, reflecting the effects of urbanisation and increased living standards. Irrigation water demand will decrease even though the irrigated area and the demand for food will increase. This can be explained by increased irrigation efficiency and, possibly, increased rainfall over the growing season (*green water availability*);
  - In terms of the availability of renewable water, total run-off will increase by 2050, as a result of climate change, but availability per capita will be nearly halved (Table 4). Hence, more water will be abstracted from renewable and non-renewable groundwater, by 2050;

- Increasingly, the demand will not be met: the water gap, being the difference between demand per capita and withdrawal per capita in Figure 3, will increase from 8% in 2010 to 18% by 2050;
- Water availability will vary widely. The areas most prone to water scarcity are the Sahel region and the Horn of Africa (see Figure 7).

Middle East and northern Africa (MENA)

- Regional analysis on volume (Figure 2):
  - A large part of the total water demand for the MENA region stems from irrigation, as food demand is growing with the increasing population;
  - Still, the increase in irrigation water demand per capita by 2050 is smaller than that in the domestic demand; the rise in irrigation water demand is partly offset by increased irrigation water efficiency and higher water availability (Figure 4; Table 4). Domestic demand rises with the growing population and increased urbanisation;
  - The demand puts the already limited water resources under more stress. The MENA region already exploits the largest share of non-renewable and therefore unsustainable, groundwater resources. In 2010, 39% of the demand is coming from non-renewable or alternative resources (Figure 4). Here, it should be observed that desalinated water, as one of the alternatives, is the largest water source in the world, although its contribution is dwarfed by the other alternatives. This underlines that, at the moment, desalinated water is a limited source of drinking water and has only limited potential for further, large-scale water provision.
- Regional analysis per capita (Figure 3):
  - The MENA region has a relatively low water demand per capita, in part reflecting the limited availability of water in this arid to semi-arid region;
  - The available amount of renewable run-off is low, amounting only to 283 m^3 per capita, per year, by 2050. This amount remains virtually unchanged compared to that in 2010, because the increase in run-off (Table 4) is counterbalanced by population growth;
  - Yet, this water availability is well below the threshold of 500 m^3 per capita, per year, a level below which limited water availability becomes economically debilitating (Table 2);
  - The withdrawal from renewable water resources increases with increased availability, but the supply will decrease, per capita, towards 2050. This will result in a slightly larger water gap, with 25% of the demand not being met by withdrawals in 2050, compared to 21% in 2010, making the MENA consistently the world's most water-scarce region.

Western and Central Europe

- Regional analysis on volume (Figure 2):
  - Western and Central Europe stand out by the large industrial water demand, which will increase further towards 2050;
  - Irrigation water requirements are relatively low, but will nevertheless increase to a certain degree, by 2050, reflecting lower water availability at higher latitudes, as a result of climate change.
- Regional analysis per capita (Figure 3):
  - The increase in total water demand is less than that in the total population and, as a result, the per-capita total water demand decreases slightly from 527 to 517 m^3 per capita, per year;
  - Domestic water demand is large for Western and Central Europe, yet the per capita domestic water demand is decreasing and reflects increased efficiency[5];
  - Water availability will not be severely affected by 2050, and the water gap even decreases from 12% in 2010 to 4% in 2050, albeit that this demand will partly be met by non-renewable groundwater;
  - Under the SSP2 scenario and the associated climate change of RCP4.5, the freshwater supply will be sufficient to meet the demand in Western and Central Europe, even in light of strongly reduced low flows in the major rivers, such as the Rhine and Danube simulated here, during the summer (cf. Pechlivanidis et al., 2017). However, this increasingly exposes the regional population to drought.

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[5] A similar trend can be observed in other developed regions of the world (e.g. North America, Japan and Oceania)

Russia and Central Asia

- Regional analysis on volume (Figure 2):
  - Developments in Russia and Central Asia reflect those described for Western and Central Europe, in terms of total volumes and amounts per capita. Noteworthy is that, for this region, water demand is high, amongst the highest in the world, which can be attributed largely to industrial water demand in Russia;
  - Water availability is not a limiting factor and non-renewable groundwater withdrawal will increase by a small amount. Thus, the water gap will decrease from 17% in 2010 to 10% by 2050, for the region as a whole, despite regional increases in demand (see Figure 7).

China and Koreas

- Regional analysis on volume (Figure 2):
  - For China and the Koreas, total irrigation water demand is high and dominated by wet rice cultivation (paddy), and this demand will increase towards 2050;
  - At the same time, domestic water demand will decrease slightly, as a result of increased efficiency.
- Regional analysis per capita (Figure 3):
  - This is the only region experiencing a strong decrease in population, which will lead to a larger per-capita demand, by 2050, of 520 m^3 per capita, per year;
  - Water availability is not a limiting factor: renewable water resources are just above the threshold of 1,700 m^3 per capita, per year, in Falkenmark et al. (1997; Table 2);
  - The water gap will decrease, from 10% in 2010 to a mere 4% by 2050, although this is achieved by a nearly 50% increase in unsustainable abstractions from the non-renewable groundwater store;
  - Groundwater depletion is predominantly a factor in the North China Plain, where most of the food production is concentrated (see Figure 6).

South Asia

- Regional analysis on volume (Figure 2):
  - This region contains the Indian Peninsula and covers the basins of the Ganges, Brahmaputra, and Indus. The region will experience a 45% increase in population and water demand by 2050, relative to 2010. As a result, domestic water demand will triple;
  - The increase in irrigation water requirements is more modest (12%), but still dominates the total demand. This limited increase partly reflects increased efficiency and water availability, although possible negative effects on food production may exist and have important consequences for food security.
- Regional analysis per capita (Figure 3):
  - The domestic water demand per capita is inflated by the increased standard of living;
  - Under RCP4.5, the effects of population change and climate change align; the water availability increases proportional to the population and the overall water availability per capita remains almost unchanged, at around 1,300 m^3 per capita, per year;
  - This classifies the region as being under looming water scarcity (Table 2). The regional water gap remains unchanged at 10%, although the dependence on surface run-off will increase, compared to that on groundwater. On the one hand, this reduces the amount of unsustainable groundwater use, but removes some of the natural buffering quality of groundwater stores, on the other (Taylor et al., 2013);
  - Strong regional differences exist; the Indus Valley being more prone to water scarcity because of more arid conditions and larger irrigation water requirements (see Figures 6 and 7). Additional investment in reservoir capacity may be required to ensure sufficient water and food supply in this region.

Southeast Asia

- Regional analysis on volume (Figure 2):
  - Southeast Asia reveals a trend similar to that in South Asia and China and the Koreas. Again, paddy irrigation dominates and its increase, relative to 2010, will be lower than that in population by 2050 (10% versus 25%; Figures 2 and 4);

- Domestic water demand will nearly double and industrial demand will also increase, although more modestly.
- Regional analysis per capita (Figure 3):
  - Population growth will slightly exceed that in water demand and the per-capita water demand will falls, slightly, staying close to the global average, at 475–500 m^3 per capita per year;
  - Water availability will keep pace with the increased demand, on a regional scale, no water gap will develop, and all water use is sustainable, in the long term.

<u>Japan and Oceania</u>
- Regional analysis on volume (Figure 2):
  - Japan and Oceania will experience virtually no population change, conform the overall trend of increased efficiency in the developed world;
  - Domestic and industrial water demand will decrease strongly (by 61% and 26%, respectively), whereas total irrigation water demand will increase (by 12%).
- Regional analysis per capita (Figure 3):
  - As irrigation water demand dominates, the per capita demand will decrease by 13%, and the 2050 demand is still among the largest of the world (only surpassed by that in North America and Russia);
  - Per-capita availability is large, but, local water scarcity will occur frequently in parts of Australia (see Figure 7);
  - Thus, a water gap exists, but this will decline from 24% in 2010 to 11% by 2050, largely reflecting the greater water availability under RCP4.5, for the region as a whole. No appreciable changes in the provenance of the water can be observed.

<u>North America</u>
- Regional analysis on volume (Figure 2):
  - In North America, water demand is largest from the industrial sector, with that from irrigation and households remaining roughly equal, between 2010 and 2050;
  - Domestic water demand will nearly halve, because of improved efficiency, but that from irrigation and industry will increase by 35% and 45%, respectively (Figure 2);
  - The total in renewable water resources will remain the same and be sufficient to meet the demand in most places, except for that in the more arid regions, where the demand for irrigation water is high, such as Central Valley and the High Plains, extending into the upper Midwest of the United States and Canada (see Figure 7). In these regions, a substantial amount is and will remain to be withdrawn from non-renewable groundwater, amounting to 5% in both 2010 and 2050, for the region as a whole (see Figure 6).
- Regional analysis per capita (Figure 3):
  - In North America, the population will increase by 30%, and total per-capita water demand will remain virtually unchanged at ~1,270 m^3 per capita, per year;
  - Substantially more water will be abstracted by 2050 and the overall water gap will close, from 20% in 2010 to 10% by 2050. This implies that, although water scarcity is widespread, it is also a local phenomenon, which is why, in other places, the increase in total demand as a result of population growth can still be met with the available resources.

<u>Central and South America</u>
- Regional analysis on volume (Figure 2):
  - Central and South America will experience an equal increase of 25% in population and water demand (Figure 2), which is just below the global average (Table 3);
  - The increases in industrial demand and irrigation demand will be comparable, whereas domestic water demand will decrease, slightly;
  - Water demand and availability are spread unevenly over this region, with the tropics having low demand but large availability, whereas the situation is reversed in the drier regions of South and Central America, where water demand from livestock and irrigation is much larger.
- Regional analysis per capita (Figure 3):

- Total water demand, per capita, will remain relatively constant, at roughly half the global mean (275 $m^3 \cdot capita^{-1} \cdot year^{-1}$), the lowest amount after sub-Saharan Africa.
- In the drier regions of South and Central America, a substantial amount of water is abstracted in non-renewable groundwater, and, for the region as a whole, its contribution will increase from 5% in 2010 to 7% by 2050.
- The largest contribution comes from surface water and there is ample supply, with the water gap of 10% in 2010 being virtually absent by 2050. Although the outlook for this region is therefore generally positive, local areas of increased and frequent water scarcity will remain (see Figure 7).

1.1.4.3 Sustainability and reliability of water supply

Reliability and sustainability of the water supply per water province was evaluated:

- Reliability was evaluated by looking at the fractional contribution from renewable and non-renewable resources (Figure 5);
- Sustainability of the supply was evaluated by looking at the groundwater footprint ratio between groundwater consumption and net recharge.

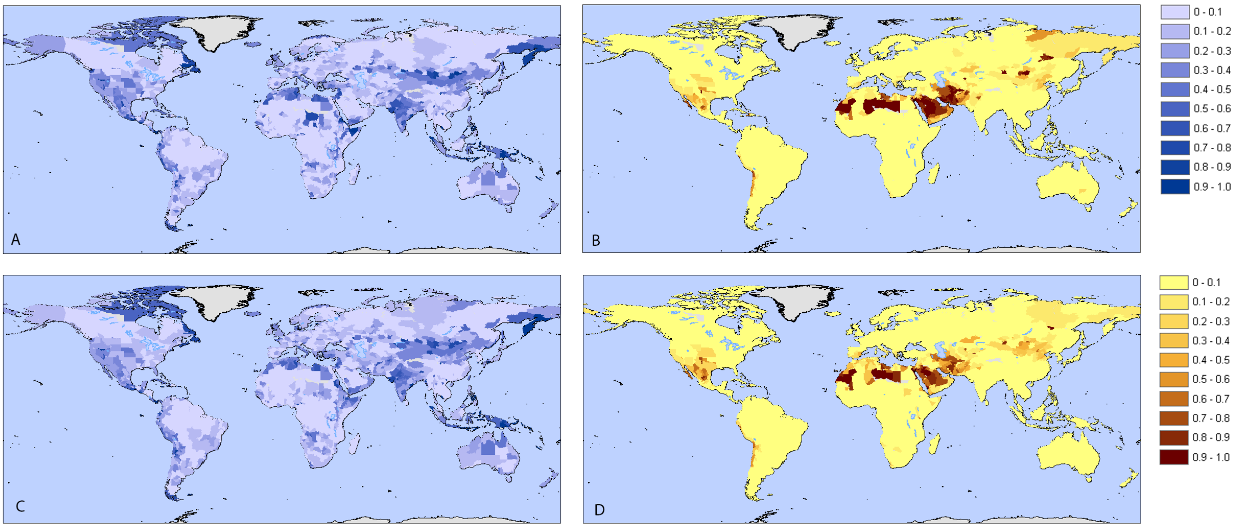


Figure 5. Fractional contribution of groundwater to total water withdrawal per water province. Values are given for withdrawals from renewable and non-renewable groundwater stocks, for the index years 2010 and 2050; with surface water abstraction and desalinisation, the latter being negligible, the values sum to unity: (a) fractional contribution of renewable groundwater for 2010, (c) idem for 2050; (b) contribution of non-renewable groundwater for 2010, (d) idem for 2050. Areas without water abstraction have been masked.

Figure 5 shows that, for most of equatorial South America and Africa, water is withdrawn mostly from surface water. Over Southeast Asia and the temperate areas of North America and Europe, considerable amounts, up to half of the total withdrawal, are abstracted from *renewable groundwater* stores. Overall, there is little difference between 2010 and 2050, indicating that the water supply in these areas is fairly secure and not affected negatively by climate change.

More variation can be observed for *non-renewable groundwater* abstraction, which is more variable and changes considerably from 2010 to 2050. Particularly over dryland areas with irrigation, a substantial amount of the withdrawal stems from unsustainable, non-renewable abstractions. This is particularly the case over the Middle East but also in parts of India and Pakistan, north-eastern China, and the High Plains in the United States and neighbouring parts of Canada and Central America, areas that are crucial for securing regional and global food supply. By 2050, these ratios will decrease somewhat, as the groundwater recharges increase slightly under the intensification of the global hydrological cycle under the impact of climate change. The largest changes are concentrated over the monsoon belt, particularly over

Central Asia, where the groundwater supply becomes more reliable. Similarly, small differences can be observed at high latitudes, where groundwater recharge increases under climate change as a result of the earlier snowmelt.

The global distribution of the fractional contribution from renewable and non-renewable resources in Figure 5 is mirrored by the groundwater footprint ratio in Figure 6. Groundwater footprint ratio values will decrease slightly by 2050. Still, the ratio will remain above unity over large areas and, here, groundwater will ultimately be depleted, threatening the supply of irrigation water and food production in these regions.

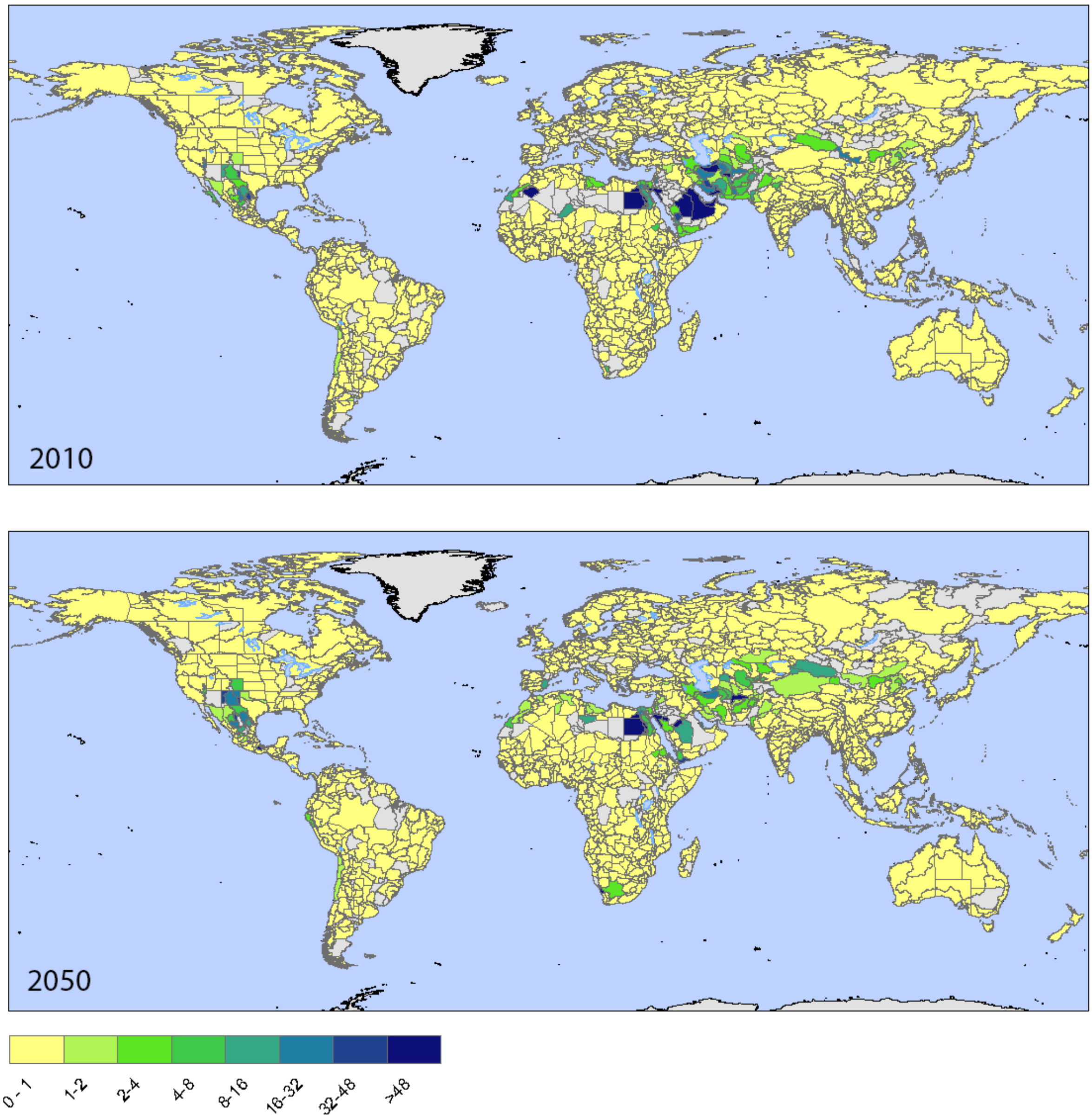
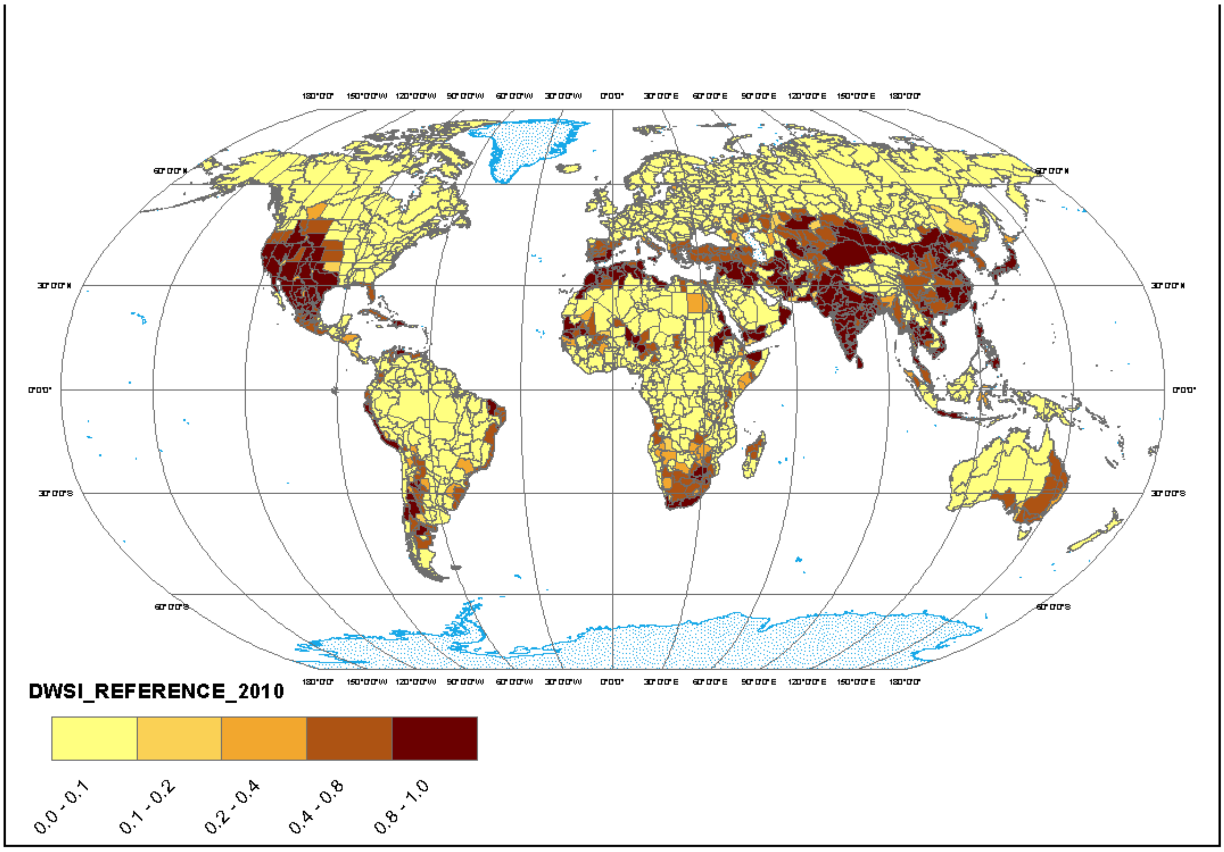


Figure 6. Groundwater footprint ratio between groundwater consumption and net recharge per water province, for the index years 2010 and 2050. Areas with an abstraction < 2 mm/year or without recharge have been masked.

1.1.4.4 Water scarcity

The dynamic water scarcity (which accounts for temporal variations in availability and demand, and thus for temporal variability in water stress; Figure 7) mirrors the distribution of non-renewable groundwater withdrawals, as this resource becomes more heavily taxed when others are unavailable. Overall, the regions experiencing water scarcity are more widespread and extend particularly into dryland areas of the Midwestern United States, Central and South America, South Africa, Southeast Asia and Australia. The distribution in 2050 will be very similar, but the DWSI will decrease over the Middle East and Central Asia, as a result of increased recharge and higher water availability, while the DWSI will increase over some of the temperate regions of North America, Europe, and East Asia.



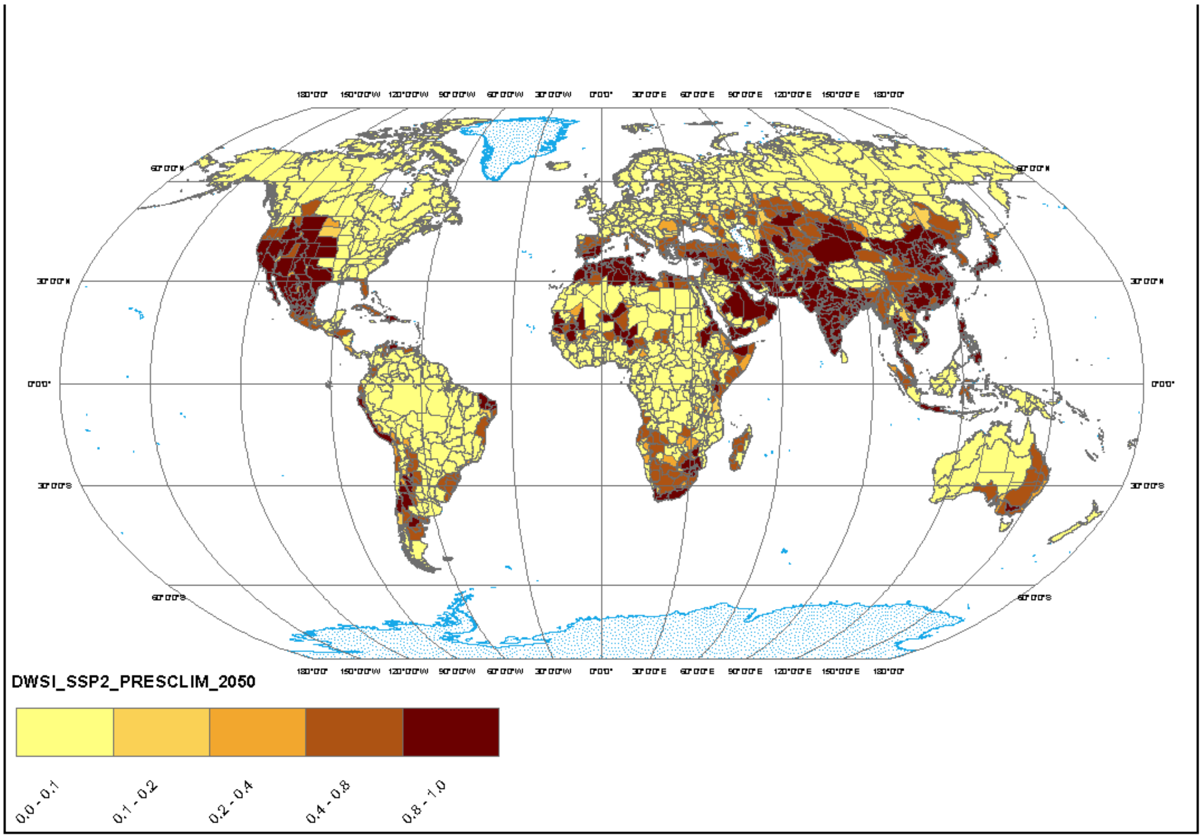


Figure 7. Dynamic Water Scarcity Index (DWSI) per water province for 2010 and 2050. Classes range from no water scarcity (DWSI < 0.1), potential water scarcity (0.1 ≤ DWSI ≤ 0.2), looming water scarcity (0.2 ≤ DWSI ≤ 0.4) to experiencing water scarcity (0.4 ≤ DWSI ≤ 0.8), economic development is limited by water scarcity (0.8 ≤ DWSI).

Still, over large parts of the globe, water scarcity is high, indicating actual water scarcity or even scarcity that is economically debilitating. In terms of projected population growth and the associated growth in water demand (Figure 2), particularly in the Sahel, the Horn of Africa, the MENA and South Asia, stand out as areas under stress, where the population is at an elevated risk of water scarcity. The same holds for more developed regions, such as the United States, Mexico, Brazil and China. Although water availability will increase in some parts of the world, as a result of climate change, this is insufficient to alleviate growing water demand and the frequency of droughts may rise (for example over Europe), a feature insufficiently captured by the temporally averaged analysis per region presented above (e.g. compare the trend in annual WSI per IMAGE region, presented in Figure 4: without exception, these regions show increasing trends in water scarcity).

1.1.5 Discussion

Uncertainties / restrictions

Scenario modelling intrinsically considers a single yet plausible pathway along which future developments may occur. It will never reflect true developments and, in this study, we focus on a single scenario of future developments, SSP2. The ensuing scenario uncertainty is therefore not quantified and confounded further by uncertainty that arises as a result of model structure and the parameterisation, although its findings are confirmed by other studies (see below). The following should be observed:

- The SSP scenarios and associated RCPs are projections of possible conditions in the future. By relying on a single SSP–RCP combination, the focus is on a single, plausible scenario but this ignores the scenario uncertainty in socio-economic developments and climate change. Other SSP–RCP combinations have been explored but the combination of SSP2 and RCP4.5, based on a plausible extrapolation of current and expected trends, is adopted here to give a comprehensive overview of the projected changes;
- By using the delta method to impose climate change on the model, the order and range of extreme events are preserved (e.g., low or high precipitation) and the calculations rely on observed historical climate data. This facilitates the evaluation of the changing hydrological response and its validation against past events. However, this ignores any possible changes in the frequency of extreme events as captured—although often with large uncertainty—by the direct GCM output;
- While some of the underlying IMAGE data on crop types and land cover include information on changing suitability and food demand, as well as land-use practices (irrigation efficiency), the land-cover parameterisation relies strongly on historical data and practices;
- Future technological developments in supply, such as growing reservoir capacity and water supplied from alternative sources such as desalination, are ignored or captured only to a limited extent (groundwater extraction);
- Our analysis concentrates on administrative units to aggregate water availability and demand. The presented analysis is therefore somewhat optimistic, as any limitations by infrastructure and any developments therein are ignored;
- Similarly, we opted to analyse the results for two benchmark years, 2010 and 2050 (see below). This obscures the intra- and inter-annual variations in water availability and water demand and this is only partially captured by the use of the DWSI and using a 10-year period around each benchmark year to increase the robustness of the computed indicators;
- As the analysis focuses on water availability, the water demand from the energy sector is not included. Projections of changes are very sensitive to assumptions about demand and technological developments, whereas the energy sector's water consumption is generally small; on a global scale, cooling water discharge capacity will decrease by 4.5% to 15% between now and the end of this century. However, currently, only 0.3% of global cooling water discharge capacity is being used for thermoelectric power (Van Vliet et al., 2016). Thus, there seems to be sufficient potential for thermoelectric power on a global scale, under climate change;

- This research addresses quantitative freshwater availability. The quality of the abstracted water is of equal importance (see the document on health, nutrients and water quality), but is not taken directly into account;
- The SSP2–RCP4.5 scenario explores trends in availability and demand under present-day considerations of sustainable use. Changing perceptions and possible coping strategies that can be adopted in response to the projected changes are not included but will strongly influence future developments. Including these aspects would require more data, bolder assumptions, and feedbacks between water availability, water demand, and development.

How do the results relate to other relevant studies?
Broadly, this study confirms findings of earlier studies on water scarcity and projected directions. Some differences arise due to the spatial units used to assess the groundwater balance in this series; the water provinces are incomparable with transboundary aquifers, such as the overexploited aquifer of the Ganges identified by Gleeson et al. (2012). Patterns are generally comparable with water gaps found by Wada et al. (2012) on irrigation water deficiencies, for the historical period. The effects of increased water availability on reduced demands are confirmed by a climate-only analysis of future changes in irrigation water demand (Wada et al., 2013). This conclusion also holds when looking at water scarcity as a whole (Schewe et al., 2014) and the global patterns in the Water Scarcity Index (WSI) largely agree with those in other studies on 2010 (Wada et al., 2011), and in the direction and patterns of change by 2050 (Wada and Bierkens, 2014).
In terms of the demand for water, the values in Table 3, which are based on IMAGE, are consistently lower than projections made under the WFaS initiative and evaluated with various global hydrological models, including PCR–GLOBWB (Wada et al., 2016). While the uncertainty range in the levels of withdrawal simulated by the various models is large, the values used in this study are consistently closer to the SSP1 of the WFaS initiative. Despite the restrictions mentioned before, this study adds to existing studies as it looks explicitly and consistently into the trends resulting from climate and socio-economic change. As such, it reveals sensitivities, particularly with respect to climate, that have not been shown this clearly before.
A downside of the present study, however, is that it only looks at a single climate change scenario and a single model in the delta approach and, thus, does not consider the scenario and model uncertainty in climate change.

Adaptive capacities
This study does not cover explicit adaptive capacities, as it follows the SSP2 *business-as-usual* scenario, without directly evaluating the feedbacks between water scarcity and development. Yet, it is certain that water management measures will be implemented on local, regional, national and international levels to secure water availability, even if the projections of socio-economic change under SSP2 will fully come to pass in practice. The capacity for actors to adapt to these changes depends on many factors, and the available measures can be ranked from low to high levels, in terms of their impact and ambition. Here, it suffices to list the important technological means that are widely applied and stimulated to increase water availability, which is in line with the storyline of SSP2. These measures include:

- Increased reservoir capacity: the construction of new reservoirs is widely planned, particularly with the objective to meet the demand in renewable energy from hydropower (Zarfl et al., 2015), but also with the primary or secondary objective to provide water downstream, particularly for irrigation. As such, such reservoirs can have a large impact—both intentionally and inadvertently—on the hydrological function of a river basin (Haddeland et al., 2014). Particularly, in those places where downstream areas are negatively affected by a change in the timing and amount of river flow due to changes in snowmelt, such as in the western mountain ranges of the United States and the major rivers of South Asia (Immerzeel and Bierkens, 2012), reservoir construction is often an efficient and preferred means to improve water availability, although social and environmental costs may be high;
- Groundwater provides a generally invisible resource that supports development, in many parts of the world (Kemper, 2004). Its development and management are key, especially when, in the future, climate change could make surface water resources less reliable and groundwater could provide a strategic buffer (Tsur, 1990). However, groundwater use can be environmentally

unsustainable, and groundwater depletion is a global problem (Konikow and Kendy, 2005), which ultimately may make groundwater unattainable or may lead to critical decreases in river flow, from an ecological perspective (Gleeson and Richter, 2017). Hence, groundwater development and management should be aimed at sustainable use, safeguarding this resource also for future generations (Hiscock et al., 2002). Vast, non-renewable reserves of groundwater are a tempting resource for development (Wada et al., 2012). For Africa and the MENA region, groundwater resources are vital to sustain future development, both in terms of providing water for the growing population projected for 2050 under SSP2, and in order to improve the quantity and quality of the water supply, which is underdeveloped, at the moment (Figure 4; Table 4). However, the potential of groundwater resources is constrained by the limited amount of recharge in the more arid regions and the prevalence of relatively low-yielding aquifers outside the larger sedimentary basins (Sahara, Congo, Kahroo; MacDonald et al., 2012). Hence, adaptation in this field requires careful planning;

- Desalination is costly, at present, and therefore limited to those areas of extreme freshwater scarcity that can afford it, such as the Gulf States and Israel, and that use it almost entirely to provide drinking water. As such, the share of desalinated water in regional and global water resources is virtually negligible (Figure 4). Yet, along the coast and near inland saltwater lakes, desalinated water can be a cost-effective source (Zhou and Tol, 2005), and new technologies and the availability of cheaper and preferably renewable energy may increase the use of this method (Elimelech and Phillip, 2011). At the same time, desalination still requires major financial investment and an extensive infrastructure, things that are often still prohibitive. At the same time, the use of desalinated water may result in environmental stress as the water volumes of inland lakes are being depleted, and the salty brine is returned to lakes or oceans, in addition to the environmental costs of building such installations and providing the energy to run them. As such, desalination—and reservoir construction—remains a controversial issue and alternative measures that reduce the demand or increase the availability of renewable water are preferred (March et al., 2014).

Other adaptive measures are available and can be evaluated, although the related choices and decisions—even in simulations—are not clear-cut and inflate the number of possible projections. For a comprehensive list of such measures with focus on the MENA region, see Droogers et al. (2012).

1.1.6 Conclusions

The map presenting dynamic water scarcity and accounting for temporal variations in availability and demand, shows that water scarcity is frequent in densely populated regions of Asia, parts of Central and South America, and in the United States. Some of these regions contain major crop producing areas (High Plains in the United States, Punjab, North China Plain). Furthermore, the scarcity indicated here has ramifications for regional and global food production. Overall, water scarcity is on the rise as a result of the growing global population and related demand. Still, this trend is partly offset by increased efficiency, particularly in domestic demand in the developed world, and, to a lesser extent, in irrigation water demand.
Imprinted on these developments is the effect of climate change. Under RCP4.5, water availability is projected to decrease in the temperate regions, whereas it is projected to increase across the monsoon areas. As a result, irrigation water requirements are projected to increase, particularly in Europe, while they will decrease over South and Central Asia. Water scarcity remains a pressing issue in the MENA region and in South and Central Asia, due to population growth, whereas temperate regions will become more prone to water scarcity as a result of increased variability. Emerging areas of increased water scarcity are Central America and particularly Sub-Saharan Africa. Although overall water availability per capita increases in Africa, the situation still remains dire and, for an increased number of people, the demand for water will remain unmet and their subsistence base will be threatened.

1.1.7 Gaps and recommendations for future research

- Here, only the physical availability of water is discussed. In addition, the amount of water that can be extracted is limited, due to technological means, political decisions (water treaties), or because of environmental concerns, and return flows of used water (i.e. *grey water)* possibly becoming too polluted for use further downstream;
- Formal definition of scenario and model uncertainty, particularly climate;
- Land-use change and feedbacks: climate and food demand interactions;
- Water withdrawal, physical infrastructure, management, and governance;
- Water quality from a human perspective and in terms of ecosystem health;
- Projections of reservoir capacity and operations;
- Groundwater flow, abstraction, and limits to feasible extraction;
- Water within trade networks of food and other goods.

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