

Interim Report

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BUILDING GLOBAL WATER USE SCENARIOS

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Abstract

The Water Future and Solutions Initiative (WFaS) develops consistent, multi-model global water scenarios with the aim to analyze the water-food-energy-climate-environment nexus and identify future hotspots of water insecurity and related impacts on food and energy security. WFaS coordinates its work with on-going scenario development in the fifth assessment review of the Intergovernmental Panel on Climate Change (IPCC), which has developed climate scenarios based on the Representative Concentration pathways (RCPs) and alternative futures of societal developments described in the Shared Socio-economic Pathways (SSPs). In its ‘fast-track’ scenario assessment WFaS applies available multi-model ensembles of RCP climate scenarios and population, urbanization, and economic development quantifications of the SSPs. Here we interpret SSP narratives to indicate direct or indirect consequences for key water dimensions. Critical scenario assumptions are assessed for different conditions in terms of a country or regions ability to cope with water-related risks and its exposure to complex hydrological conditions. For this purpose a classification of hydro-economic challenges across countries has been developed. Scenario assumptions were developed for defined categories of hydro-economic development challenges and relevant features of SSPs. In this way we systematically assess qualitatively key scenario drivers required for global water models. We then provide quantifications of assumptions for technological and structural changes for the industry and domestic sector. For the quantification of global scenarios of future water demand, we applied an ensemble of three global water models (H08, PCR-GLOBWB, WaterGAP). Ensemble results of global industrial water withdrawal highlight a steep increase in almost all SSP scenarios. Global amounts across the three models show a wide spread with the highest amounts reaching almost $2000 \text{ km}^3 \text{ yr}^{-1}$ by 2050, more than doubled compared to the present industrial water use intensity ($850 \text{ km}^3 \text{ yr}^{-1}$). Increases in world population result in global domestic water withdrawals by 2050 reaching $700\text{-}1500 \text{ km}^3 \text{ yr}^{-1}$ depending on scenario and water model. This is an increase of up to 250% compared to the present domestic water use intensity ($400\text{-}450 \text{ km}^3 \text{ yr}^{-1}$). We finally suggest improvements for future water use modelling.

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Professor Fischer is recognized as one of 23 IIASA scientists that have contributed to the large body of IPCC reports. The Nobel Peace Prize (2007) was awarded to the Intergovernmental Panel on Climate Change (IPCC) and Al Gore for "their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change."

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PhD candidate in University of Tokyo, Japan. In his research he applied a global land surface model which includes human activities such as reservoir, irrigation and water demand, and I have assessed impact of both climate change and human activity on terrestrial water cycle, especially drought. I believe that my result is informative to decision making. During his academic career he worked on an "Assessment of Virtual Water Trade in Hokkaido with inter-industry relations table", analysing transport of virtual water by a method of economic statistics, a "Study on impact of Land Use Change on regional scale precipitation in Northeast China", including a numerical experiment using a meso-scale numerical weather prediction system and finally a "Study on impact of the water resources management on projected future change of drought" which he dedicated his Ph.D to including a global scale impact assessment of climate change focusing on hydrological drought using land-surface model that discussed impact and benefit of human activity for water resource.

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Naota Hanasaki, a senior researcher at the Center for Global Environmental Research of the National Institute for Environmental Studies, ... Research expertise surround Global hydrological modeling incorporating major human activities, Climate change impact assessment on water sectors , Integrated assessment modeling, Earth system modeling. In its studies, IIASA applies a global water resources model called H08, developed by Naota Hanasaki. H08 is an open source global hydrological model with major human activities. Source code, manuals, and the latest information are available.

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The Water Futures and Solutions Initiative is a broad-based international consortium with the long term goal of providing the systems analytical frameworks and tools to identify and assess sustainable, robust, no-regret portfolios of options, which are coherent across sectors and management scales, for the purpose of improving human well-being through enhanced water security, under the range of possible futures and uncertainties faced by society. Broad-based participation of the water community, and the communities of related sectors, is critical for not only advancing knowledge and science, but also for providing consistent messages on which decision makers across sectors and scales of management can act to produce consistent implementation of portfolios of solutions. We therefore would like to acknowledge and thank the partners that helped launch the initiative: IIASA, UN-Water/UNESCO, the World Water Council (WWC), the International Water Association (IWA), and the Ministry of Land, Infrastructure and Transport (MOLIT) of the Republic of Korea. We also thank the many organizations that have contributed as part of the consortium (*see blue-box below*).

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1. Introduction

One of the primary tasks of the Water Futures and Solutions (WFaS) initiative is to develop global scenarios of water potentials and stressors, their interdependencies across the different sectors, the climate-water-food-energy-ecosystem nexus, and the impacts on human wellbeing and earth ecosystems and the services they provide. In the quantitative analysis WFaS develops consistent, multi-model global water scenarios with the aim to analyze the water-food-energy-climate-environment nexus and identify future hotspots of water insecurity and related impacts on human well-being, in particular food and energy security.

The WFaS initiative coordinates its work with other on-going scenario efforts in the context of the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR5) (Moss, et al., 2010) for the sake of establishing a consistent set of new global water scenarios. The emission scenarios of the Representative Concentration Pathways (RCPs) (van Vuuren, et al., 2011) were completed in 2012 and provide input that is essential for climate modelers. The spatial and seasonal patterns of future climate change estimated by climate models must be complemented by socioeconomic and ecological data that the other climate change research groups, namely the integrated assessment modelers (IAM), and the impacts, adaptation, and vulnerability community need. In response to this the climate change research community converged on new projections, termed *Shared Socioeconomic Pathways* (SSPs) (O'Neill, et al., 2015) (O'Neill, et al., 2014) (O'Neill, et al., 2011). Very few assessments have used the SSPs to assess the impacts of global change on water resources, e.g. (Hanasaki, et al., 2013)¹, (Arnell & Lloyd-Hughes, 2014).

The WFaS global water scenario assessment framework has initially followed a 'fast-track' mode to produce well-founded yet preliminary scenario estimates. It extends the SSP storylines with a water dimension and makes use of available results of climate projections² based on the four RCPs and socio-economic developments based on the five SSPs to develop a set of (preliminary) quantitative water projections. These climate and socio-economic pathways are being analyzed in a coordinated multi-model assessment

¹ Hanasaki et.al (2013) focused on technology change and environmental consciousness as prescribed by the SSP narratives to determine a qualitative assessment of key assumptions required for water use scenarios and literature based quantified variables for application in water use scenario analysis.

² Distributed by the Coupled Model Intercomparison Project (CMIP), see <http://cmip-pcmdi.llnl.gov/cmip5/>

process involving sector and integrated assessment models, water demand models and different global hydrological models.

State-of-the-art global water use models will be forced with available future projections of population, urbanization, economic growth and energy consumption for each SSP and country. Next to these exogenous drivers, global water use models calculate future water demand and use based on a set of assumptions mainly related to technological and structural changes. The aim of this paper is to describe the process of developing these additional assumptions that critically determine future water use.

In the second section we first present the WFaS scenario approach (Chapter 2), followed by the implementation separately for each main water use sector, industry (Chapter 3) domestic (Chapter 4) and agriculture (Chapter 5). We also provide quantifications of assumptions for technological and structural changes for the industry and domestic sector. Respective quantifications for the agricultural sector are more complex and presented elsewhere. In Chapter 6 we summarize drivers and assumptions applied in the WFaS ‘fast-track’ assessment and present preliminary results for future industrial and domestic water demand. We finally conclude (Chapter 7) with key findings and suggest next steps for further improving future water scenario assessments.

2. Scenario approach

2.1 Building scenarios in Water Futures and Solutions (WFaS)

Alternative scenarios are an important method for exploring uncertainty in future societal and interrelated environmental conditions. The WFaS global water scenarios follow the SSP storylines, apply available quantification of socioeconomic variables from the SSP database (IIASA, 2015), and extend critical water dimensions (Cosgrove, et al., 2015). The SSPs designed to offer the possibilities for experimentation by a wide range of researchers on extending the basis SSPs in various dimensions (O'Neill, et al., 2014).

Developed by the climate change community, the key elements of the SSP narratives focus on climate policy analysis. Thus narratives include less or maybe even no information relevant for the water sector. We contribute here by extending the SSPs with relevant critical dimensions of the main water use sectors industry, domestic, and agriculture for the development of a first set of assumptions applied in global water models.

A global assessment is essential in view of the increasing importance of global drivers such as climate change, economic globalization or safeguarding biodiversity. Maintaining a global perspective and provide the necessary regional detail to identify future pathways and solutions is key for water scenario development. Against this background, WFaS aims for its quantitative scenario assessment not only a high level of regional detail (typically at the grid-cell level) but also to go beyond globally uniform assumptions of important scenario drivers.

This is achieved for different conditions in terms of a country or regions ability to cope with water-related risks and its exposure to complex hydrological conditions. For this

purpose a classification of hydro-economic challenges across countries has been developed (Fischer, et al., 2015). In this way, countries and/or watersheds can assume varying scenario drivers (e.g. technological change rates) for defined categories of hydro-economic development challenges. Critical water dimensions have been assessed qualitatively and quantitatively for each SSP and hydro-economic class. The quantification determines assumptions for variables required in state-of-the-art global water models.

The WFaS project extends the use of participatory processes to scenario development. Stakeholders and experts are asked to develop and refine qualitative storylines for the scenarios and to provide qualitative and quantitative estimates of changes in some of the factors affecting freshwater resources now and in the future. In WFaS the following stakeholder groups play an active role in the scenario development process:

- (i) The Scenario Focus Group (SFG), a representative group of stakeholders whose role is to provide guidance to ensure the global and regional relevance and legitimacy of the scenarios and
- (ii) The Sector Actors Group (SAG), a stakeholder group which enriches and grounds the water scenarios by providing a range of sector perspectives and considerations during their development, to ascertain the feasibility of the scenarios. The SAG will also develop portfolios of solutions for the main global challenges.
- (iii) In addition, regional stakeholder groups will focus on respective geographic areas. IIASA, together with the Asian Development Bank, is building a regional stakeholder consortium for Asia, and the Water Futures and Solutions Initiative has established case studies, which have their own stakeholder groups, in other parts of the world

Overall, the scenario development is based on the SAS (Story And Simulation) approach linking storyline revision and modeling work in an iterative process. These different groups of stakeholders will broaden and enrich the analysis and assumptions.

A first stakeholder meeting has reflected on the scenario approach (Magnuszewski, et al., 2015). Additional stakeholder involvements will provide important sounding boards for developing a second round of stakeholder-driven multi-model assessments.

2.1 The water dimension in the Shared Socio-Economic Pathways

The Shared Socio-Economic Pathways (SSP) include both a qualitative component in the form of a narrative on global development and a quantitative component that includes numerical pathways for certain variables that are particularly useful to have in quantitative form for use in other studies. Narratives were developed and agreed upon for basic versions of five SSPs, illustrated in Figure 1 within the space of socio-economic challenges to mitigation and adaptation outcomes that the SSPs are intended to span. Each narrative includes a summary and a full version. Box 1 provides an excerpt of the summary of each storyline.

For each SSP “elements” were identified to describe a set of variables, processes, or components of human-environment systems that provide the building blocks for constructing both the qualitative and quantitative aspects of SSPs. Key elements of an SSP characterize the global socio-economic future of the 21st century as a reference for climate change analysis. They include demography, economic development, human development, technology, lifestyles, environment and natural resources, and policy and institutions. For a subset of SSP elements an associated table of qualitative assumptions for all SSPs about direction and magnitude of trends in SSP elements were developed (Annex III in (O’Neill, et al., 2011)).

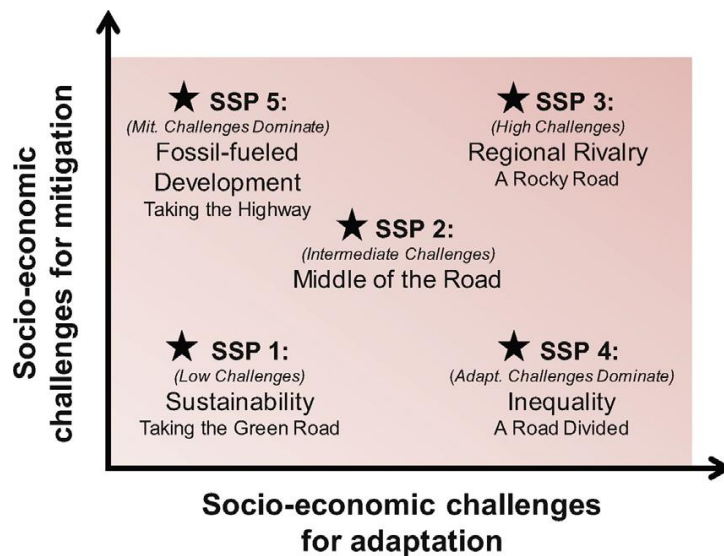


Figure 1: The shared socioeconomic pathways (SSPs) representing different combinations of challenges to climate mitigation and adaptation. Source: (O’Neill, et al., 2015)

Here we extend the SSP storylines with a water dimension and develop “water extended SSP storylines”. The SSP element list in (O’Neill, et al., 2015) includes an element group ‘environment and natural resources’. However, no water aspect has been included in the qualitative ranking. Throughout the storylines particular reference to freshwater is rare, mainly discussed in the context of ‘access to safe water’. Selected SSPs refer to ‘water pollution’ (SSP5) or ‘water insecurity’ (SSP1, SSP2).

We’ve first scrutinized the SSP storylines to identify key variables relevant for the different water use sectors. Each SSP describes a specific set of variables. To achieve a comprehensive overview we’ve appended our own interpretation (green colored text in Annex I) for variables lacking in selected narratives.

Box 1. Shared Socioeconomic Pathways (SSP)

SSP1: Sustainability – Taking the green road

“The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Increasing evidence of and accounting for the social, cultural, and economic costs of environmental degradation and inequality drive this shift. Management of the global commons slowly improves, facilitated by increasingly effective and persistent cooperation and collaboration of local, national, and international organizations and institutions, the private sector, and civil society.”

SSP2: Middle of the road

“The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Most economies are politically stable. Globally connected markets function imperfectly. Global and national institutions work toward but make slow progress in achieving sustainable development goals, including improved living conditions and access to education, safe water, and health care. Technological development proceeds apace, but without fundamental breakthroughs.”

SSP3: Regional rivalry – A rocky road

“A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. This trend is reinforced by the limited number of comparatively weak global institutions, with uneven coordination and cooperation for addressing environmental and other global concerns. Policies shift over time to become increasingly oriented toward national and regional security issues, including barriers to trade, particularly in the energy resource and agricultural markets. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development, and in several regions move toward more authoritarian forms of government with highly regulated economies. Investments in education and technological development decline.....”

SSP4: Inequality – A road divided

“Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally-connected society that is well educated and contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor intensive, lowtech economy. Power becomes more concentrated in a relatively small political and business elite, even in democratic societies, while vulnerable groups have little representation in national and global institutions.....”
(O'Neill, et al., 2015)

SSP5: Fossil-fueled development – Taking the highway

“Driven by the economic success of industrialized and emerging economies, this world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated, with interventions focused on maintaining competition and removing institutional barriers to the participation of disadvantaged population groups.....”

Source: (O'Neill, et al., 2015)

2.2 Hydro-Economic classification for regional differentiation of scenario drivers

Maintaining a global perspective and provide the necessary regional detail to identify future pathways and solutions is key for water scenario development. Against this background, WFaS aims for its quantitative scenario assessment not only a high level of regional detail (typically at the grid-cell level) but also to go beyond globally uniform assumptions of important scenario drivers. This requires developing a system of classification for countries and watersheds describing different conditions pertaining to water security (or its reverse water challenges). We've developed a compound indicator based methodology for the classification of countries (and watersheds) into a two-dimensional hydro-economic space. In this way, countries and/or watersheds can assume varying scenario drivers (e.g. technological change rates) for defined categories of hydro-economic development challenges.

The hydro-economic classification consists of two broad dimensions representing respectively

- (i) a country's/region's economic and institutional capacity to address water challenges; i.e. the economic institutional capacity (y-dimension)
- (ii) a country's/region's magnitude / complexity of challenges related to the management of available water resources; i.e. hydrological challenge/complexity (x-dimension)

For the classification, each major dimension is measured by a normalized composite index, which is computed from a set of relevant indicators. In this way countries/regions will be located in a two-dimensional space representing different human-natural water development challenges and levels of water security.

For example, for the estimation of qualitative and quantification assumptions of critical water dimensions and drivers in the WFaS scenario assessment (e.g. technological change rates) we assign different values depending on the country's location in one of four quadrants in the two-dimensional space (Figure 1).

For the y-dimension, we've selected one indicator, namely GDP per caput (in constant PPP dollars per caput) as a measure of economic strength and financial resources available for investing in risk management. Another indicator initially discussed was the Corruption Perception Index (CPI) (Transparency International³, see www.transparency.org). In a first attempt the CPI was included in the compound indicator for economic-institutional capacity based on the assumption that lower corruption may indicate higher coping capacity to water related risks and vice versa. However, in response to disapproval of this indicator by a workshop of WFaS stakeholders, the CPI was excluded from the composite indicator. Moreover for determining hydro-economic classes in different future scenarios, an estimation of the CPI would be required using formal methods or expert judgments based on the information available in the scenario narratives.

³ See www.transparency.org

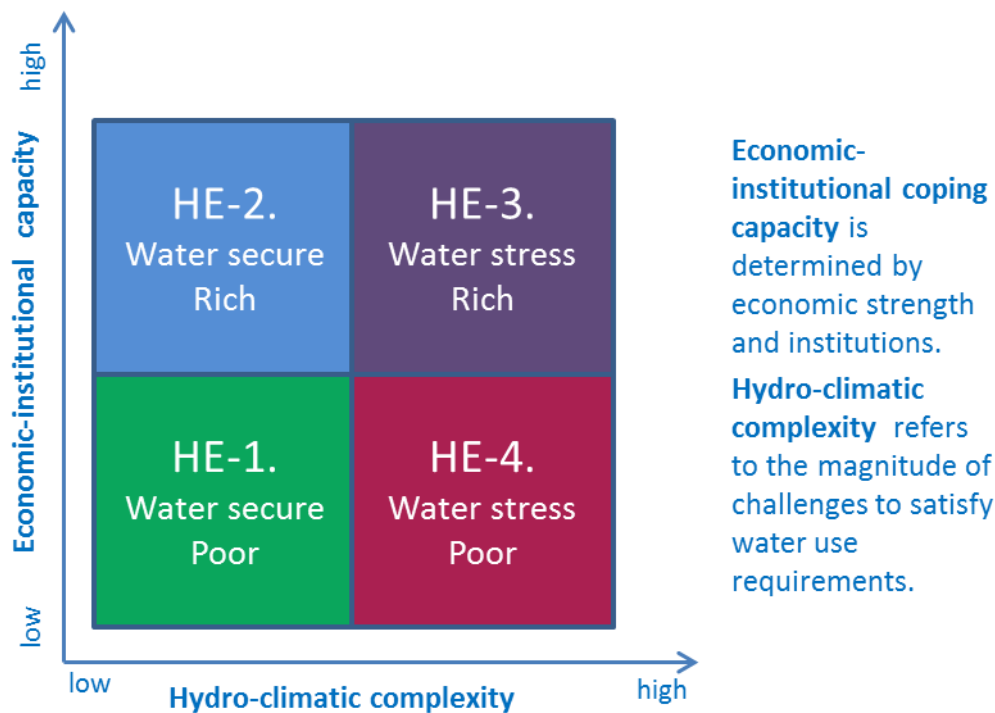


Figure 2: Conceptual framework for allocation of hydro-economic classification to four quadrants of water security

For the x-dimension of water challenge complexity, we use four component indicators:

- (i) Total *renewable water resources per capita* (in m³/person/yr) as a measure for water availability;
- (ii) The ratio of annual water withdrawal to total renewable water resources (scalar fraction) as a proxy for relative *intensity of water use*;
- (iii) *Runoff variability* expressed by the coefficient of variation of simulated monthly runoff for a 30-year period as proxy for both inter- and intra-annual variability of water resources;
- (iv) The share of external (from outside national boundaries) to total renewable water resources as a measure for the *dependency of external water resources*.

The component indicators change over time leading to varying indicators over time and potential relocation of selected countries from one hydro-economic class into another. However, in the WFaS ‘fast-track’ analysis these potential moves have not yet been employed. Instead we’ve defined one set of hydro-economic indicators for each country for the year 2000 (Fischer, et al., 2015).

3. Industrial water use

3.1 Water dimensions

Globally industrial water withdrawal amounts to 731 billion m³ per year, corresponding to about one fifth of total water withdrawal (AQUASTAT). However, in industrialized countries the share of industrial water withdrawal in total water withdrawal usually exceeds 40% (Figure 3). Water demand for industrial uses doubled since the 1960s.

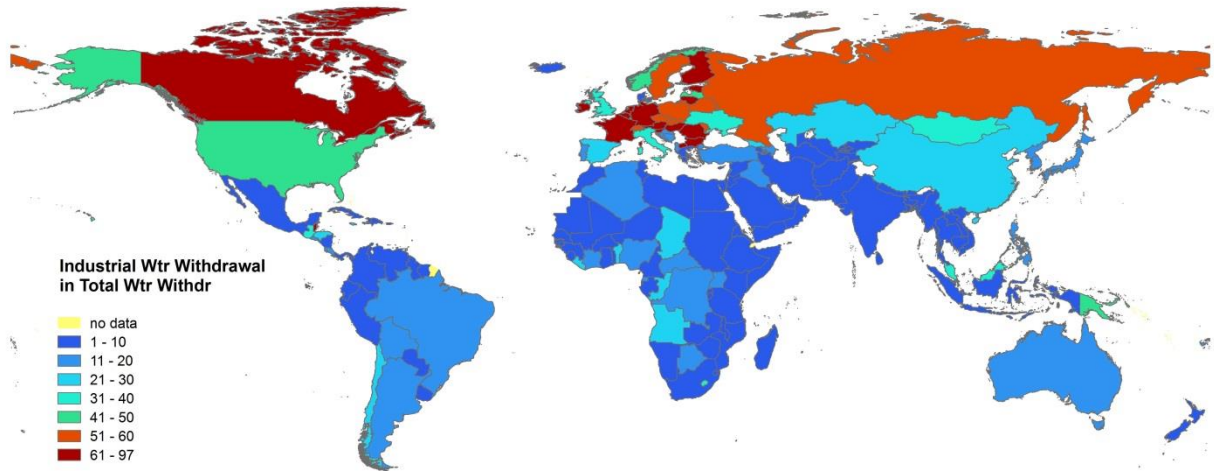


Figure 3. Share of industrial water withdrawal in total water withdrawal Source: AQUASTAT

Industrial water use includes two main components. First water for the cooling of thermoelectric plants determines water use in the *electricity sector*. Besides electricity the other main industrial water use occurs in the *manufacturing sector*.

Water use intensities describe the amount of water required to produce a unit of electricity (m³/GJ) or a unit of manufacturing (m³/Gross Value Added in Manufacturing). Future industrial water demand depends on:

- i) technological changes in the industries concerned, and
- ii) structural changes in a country's / region's industrial sector

Global water models require country specific assumptions about the future developments of electricity consumption, gross value added in the manufacturing sector (the main consumer of water in industry besides electricity generation) and technological changes rates. Depending on global water model one or more of the following input data are required:

- i) Energy consumption
- ii) Electricity consumption
- iii) Economic development
- iv) Gross Value Added in Manufacturing
- v) The impact of technological change on industry water use intensities

- vi) The impact of structural changes on industry water use intensities

The former are derived from available results of global economic and energy models. Technological change rates are determined in WFaS for each SSP and depending on the country's attribution to one of the four hydro-economic classifications.

3.2 SSP storylines and implications for industrial water use

In the following we scrutinize each SSP narrative for developments relevant for water use in the industry sector, separate for electricity and manufacturing, and interpret those in terms of implications for electricity water use intensities and extents of water use in the manufacturing sector. We first summarize for each SSP those key elements of the storylines, which impact the water dimensions of each sector (excerpts of the storylines) and then interpret those in relation to their water dimensions.

In general, the size, structure and technologies applied in the electricity and manufacturing sector and their impact on water use and water use intensities are closely linked to resource-efficiency of the economy, implementation of environmental regulations, and progress in water saving technologies.

SSP1: Sustainability – Taking the green road

Elements of the SSP storyline relevant for the ELECTRICITY sector

- ✓ reduced overall energy demand over the longer term
- ✓ lower energy intensity, with decreasing fossil fuel dependency
- ✓ relatively rapid technological change is directed toward environmentally friendly processes, including energy efficiency, clean energy technologies; favorable outlook for renewables - increasingly attractive in the total energy mix
- ✓ strong investment in new technologies and research improves energy access
- ✓ advances alternative energy technologies

Implications for electricity water use intensity

- ✓ Reduction in energy demand will decrease the demand for water from the energy sector substantially even if world population, primary energy production, and electricity generation were to increase.
- ✓ A shift away from traditional biomass toward less consumptive energy carriers, as well as the changing energy mix in electricity generation could lead to water savings.
- ✓ A favorable outlook for renewables will cause big structural and efficiency shifts in the choice of technology with variable consequences for water use intensity and efficiency, depending on the renewable type. For example, an expanding output of biofuels will lead to a rise in water consumption, whereas a shift towards photovoltaic solar power or wind energy will lead to a decrease in water use intensity.

- ✓ Higher energy efficiency could translate into a relatively lower water demand, improvements in water quality, following high standards that commit industry to continually improving environmental performance.
- ✓ Overall, structural & technological changes will result in decreasing water use intensities in the energy sector. For example the widespread application of water-saving technologies in the energy sector will significantly reduce the amount of water used not only for fuel extraction and processing but also for electricity generation as well

Elements of the SSP storyline relevant for the MANUFACTURING sector

- ✓ Improved resource-use efficiency
- ✓ More stringent environmental regulations
- ✓ Rapid technological change is directed toward environmentally friendly processes
- ✓ Research & Technology development reduce the challenges of access to safe water
- ✓ Risk reduction & sharing mechanism

Implications for manufacturing water use

- ✓ The importance of the manufacturing sector in the overall economy decreases further due to the increasing importance of the non-resource using service sector
- ✓ Manufacturing industries with efficient water use and low environmental impacts are favored and increase their competitive position against water intensive industries
- ✓ Enhanced treatment, reuse of water, and water-saving technologies; Widespread application of water-saving technologies in industry

SSP2: Middle of the road

Elements of the SSP storyline relevant for the ELECTRICITY sector

- ✓ Continued reliance on fossil fuels, including unconventional oil and gas resources
- ✓ Stabilization of overall energy demand over the long run
- ✓ Energy intensity declines, with slowly decreasing fossil fuel dependency
- ✓ Moderate pace of technological change in the energy sector
- ✓ Intermediate success in improving energy access for the poor

Implications for electricity water use intensity

- ✓ Reliance on fossil fuels may lead to only minor structural and efficiency shifts in technology
- ✓ Stabilization of overall energy demand over the long run will lead to little or no change in water demand for fuel extraction, processing and electricity generation
- ✓ A decline in energy intensity will lower water demand

- ✓ A moderate pace in technological change will cause minor structural and efficiency shifts in technology and ultimately water use intensity will change only slightly.
- ✓ Weak environmental regulation and enforcement trigger only slow technological progress in water use efficiencies.
- ✓ Regional stress points will increase globally. Power generation in regional stress points will likely have to deploy more and more technologies fit for water-constrained conditions to manage water-related risks, though this can involve trade-offs in cost, energy output and project siting.
- ✓ In general, if historic trends remain the same, water use intensities will continue to decrease in the most developed regions. However, there will be slow progress in Africa, Latin America and other emerging economies.

Elements of the SSP storyline relevant for the MANUFACTURING sector

- ✓ The SSP2 World is characterized by dynamics similar to historical developments
- ✓ Moderate awareness of environmental consequences from natural resource use
- ✓ Modest decline in resource-intensity
- ✓ Consumption oriented towards material-growth
- ✓ Technological progress but no major breakthrough
- ✓ Persistent income inequality (globally & within economies)

Implications for manufacturing water use

- ✓ Manufacturing GVA further declines in relative terms
- ✓ Moderate & regionally different decreases of manufacturing water use intensities
- ✓ Following historic trends water use intensities further decrease in the most developed regions but less progress in Africa, Latin America and other emerging economies
- ✓ Weak environmental regulation and enforcement trigger only slow technological progress in water use efficiencies

SSP3: Regional Rivalry – A rocky road

Elements of the SSP storyline relevant for the ELECTRICITY sector

- ✓ Growing resource intensity and fossil fuel dependency
- ✓ Focus on achieving energy and food security goals within their own region
- ✓ Barriers to trade, particularly in the energy resource and agricultural markets
- ✓ Use of domestic energy results in some regions increase heavy reliance on fossil fuels
- ✓ Increased energy demand driven by high population growth and little progress in efficiency.

Implications for electricity water use intensity

- ✓ Barriers in trade may trigger slow technological progress in water use efficiencies. A moderate pace in technological change will cause minor structural and

efficiency shifts in technology and ultimately water use intensity will change only slightly.

- ✓ Reliance on fossil fuels may lead to only minor structural and efficiency shifts in technology
- ✓ An increase in energy intensity will increase water demand where as little progress in efficiency would trigger increased water demand as energy use intensifies
- ✓ Weak environmental regulation and enforcement hamper technological progress in water use efficiencies, hence very low progress in water-saving technologies.

Elements of the SSP storyline relevant for the MANUFACTURING sector

- ✓ Low priority for addressing environmental problems
- ✓ Resource-use intensity is increasing
- ✓ Low investment in education and technological development
- ✓ Persistent income inequality (globally & within economies)
- ✓ Weak institutions & global governance

Implications for manufacturing water use

- ✓ Manufacturing GVA in relative terms (% of GDP) declines slower than historic trends
- ✓ Weak environmental regulation and enforcement hamper technological progress in water use efficiencies
- ✓ Very low progress in water-saving technologies
- ✓ Water use intensities increase only marginally, primarily in the most developed regions

SSP4: Inequality – A road divided

Elements of the SSP storyline relevant for the ELECTRICITY sector

- ✓ Oligopolistic structures in the fossil fuel market leads to underinvestment in new resources
- ✓ Diversification of energy sources, including carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources like nuclear power, large-scale CSP, large hydroelectric dams, and large biofuel plantations
- ✓ A new era of innovation that provides effective and well-tested energy technologies
- ✓ Renewable technologies benefit from the high technology development

Implications for electricity water use intensity

- ✓ A move towards more water intensive power generation will lead to a rise in water consumption. However, new technologies in processing primary energy, especially in the thermal electricity generation as well as an increased use of renewable energy and improved energy efficiency will have an impact on water savings.

- ✓ Rapid technical progress could trigger water efficiency improvements in the energy sector, which then will translate into a decrease in water use intensities. However the progress will be mainly in richer regions, whereas the energy sector in low income countries may stagnate, with little progress in decreasing water use intensities.
- ✓ Regional stress points will increase globally. Power generation in regional stress points will likely have to deploy more and more technologies fit for water-constrained conditions to manage water-related risks, though this can involve trade-offs in cost, energy output and project siting.
- ✓ For additional implication: ref. implications for both SSP 1 and 2 depending on the energy path. Continued use of nuclear power and large scale CSPs, for instance, will intensify water use.

Elements of the SSP storyline relevant for the MANUFACTURING sector

- ✓ Increasing inequality in access to education, a well educated elite
- ✓ Rapid technological progress driven by well-educated elite
- ✓ Persistent income inequality (globally & within economies)
- ✓ Labor intensive, low tech economy persists in lower income, poorly educated regions

Implications for manufacturing water use

- ✓ Manufacturing GVA in relative terms (% of GDP) declines in economically rich regions but decreases very slow in poorer regions
- ✓ Rapid technical progress triggers water efficiency improvements in manufacturing. However the progress is mainly implemented in rich regions.
- ✓ The manufacturing sector in low income, poorly educated regions stagnates with little progress in decreasing water use intensities

SSP5: Fossil-fueled development—Taking the highway

Elements of the SSP storyline relevant for the ELECTRICITY sector

- ✓ Adoption of energy intensive lifestyles
- ✓ Strong reliance on cheap fossil energy and lack of global environmental concern
- ✓ Technological advancements in fossil energy means more access to unconventional sources
- ✓ Alternative energy sources are not actively pursued

Implications for electricity water use intensity

- ✓ The structure of the energy sector is driven by market forces, with water intensive energy sources and technologies persisting into the future. Nevertheless, a rapid technological change may lower water use intensities
- ✓ The combined effect of structural and technological changes results in only moderate decreases in manufacturing water use intensities

- ✓ The development of unconventional oil and gas resources, which also raises notable water-quality risks, will increase water use intensity in the energy sector, especially for fuel extraction and processing
- ✓ Regional stress points will increase globally. Power generation in regional stress points will likely have to deploy more and more technologies fit for water-constrained conditions to manage water-related risks, though this can involve trade-offs in cost, energy output and project siting.

Elements of the SSP storyline relevant for the MANUFACTURING sector

- ✓ A continued large role of the manufacturing sector
- ✓ Adoption of the resource and energy intensive lifestyle around the world
- ✓ Robust growth in demand for services and goods
- ✓ Technology, seen as major driver for development, drives rapid progress in enhancing technologies for higher water use efficiencies in the industrial sector
- ✓ Local environmental impacts are addressed effectively by technological solutions, but there is little proactive effort to avoid potential global environmental impacts

Implications for manufacturing water use

- ✓ Manufacturing GVA in relative terms (% of GDP) declines only slowly
- ✓ The structure of the manufacturing sector is driven by economics with water intensive manufacturing industries persisting into the future
- ✓ Yet, there is rapid technological change in the manufacturing industry contributing also to lowering the manufacturing water use intensities
- ✓ The combined effect of structural and technological changes results in only moderate decreases in manufacturing water use intensities

3.3 Technological change rates: Qualitative and quantitative assessment

A technological change (almost) always leads to improvements in the water use efficiency and thereby decreases water use intensities in the industry (includes electricity and manufacturing) and domestic water use sectors. Water use intensities describe the amount of water required to produce a unit of electricity (m³/GJ) or manufacturing (m³ / Gross Value Added in Manufacturing).

Examples for technological changes, which improving manufacturing water use intensities include changing or modifying machinery to use less water, switching to waterless processes, or treating and reusing water. Other technological improvements include i) recovering waste heat and use it to heat the facility (instead of cooling hot machinery); ii) investing in on-site water treatment for re-use; iii) recovering water from steam boilers.

We first rate qualitatively the level of technological improvement separate for the five SSPs and four Hydro-Economic regions.

Technological change in the SSP storylines: Strong investments in new technology and research including technologies directed toward environmentally friendly processes are key in the narratives of SSP1, 4, and 5. In SSP1 and SSP5 technological progress

disseminates globally although driven by different incentives. While the sustainability paradigm of SSP1 seeks global use of enhanced technologies, the SSP5 economic development priorities favor water-efficient technologies as the cheapest option. In contrast in the SSP4 narrative the technological progress developed by well-educated elites can often not be implemented by poor regions lacking access to investment capital. Overall we assess the elite-induced technological progress (in SSP4) as somewhat lower compared to the sustainability (SSP1) and market-driven (SSP5) technological progress. In SSP2 technological changes proceed at moderate pace, but lack fundamental breakthroughs. In SSP3 low investments in both R&D and education result in only slow progress in technological changes.

Technological change in the Hydro-Economic [HE] regions: Limited access to investment in the poor countries of the Hydro-Economic regions HE-1 and HE-4 is a major barrier for the implementation of new technologies. However the difficult hydro-climatic conditions in HE-4 force even poor countries to spend some of their limited available capital for implementing new technologies leading to higher progress in technological change compared to HE-1 where water is abundant. The rich countries of HE-2 and HE-3 have the economic and institutional potential to invest in and transfer to state-of-the-art technologies. Yet, in countries of the water-scarce region HE-3 the urgency to implement water-saving technologies result in stronger decreases of water use intensities driven by technological improvements compared to HE-2, which would also have the means to implement new technologies but lack the incentive due to sufficient water resources.

Combine SSP and HE: Second we regroup the combinations of the SSP and HE ratings into seven groups A to E indicating a decreasing speed of technological progress. A signifies the highest decreases in water use intensities due to technological changes and E the lowest decreases, i.e. water use efficiencies improve fastest in A and slowest in E. Assigning of the combined SSP, HE ratings to a group depends on the weight attached to the first-order SSP and HE ratings. The global dissemination of technological progress in SSP1 and SSP5 suggests to weigh the SSP higher compared to the first-order HE ratings ('SSP dominant'). Moreover SSP1 seeks development pathways directed towards reducing inequality globally. In contrast SSP3 and SSP4 are characterized by fragmentation and large disparities across countries and we therefore assign for the scenario assumptions a higher importance to the HE rating compared to the SSP rating ('HE dominant'). For SSP2 we assume an equal importance of the SSP and HE ratings ('SSP as HE').

**The effect of technological changes on water use intensities
in the INDUSTRY sector**

			L		M		H		M	
		<i>socio-economic capacity</i>	poor		rich		rich		poor	
		<i>hydro-climatic complexity</i>	low		low		high		high	
			HE-1		HE-2		HE-3		HE-4	
H	SSP1	Sustainability (SSP dominant)	HL	B	HM	B	HH	A	HM	B
M	SSP2	Historic paths (SSP as HE)	ML	D	MM	C	MH	B	MM	C
L	SSP3	Fragmentation (HE dominant)	LL	E	LM	D	LH	C	LM	D
M	SSP4	Inequality (HE dominant)	ML	D	MM	C	MH	B	MM	C

H	SSP5	Market first dominant)	(SSP	HL	B	HM	B	HH	A	HM	B
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Source: WFaS/IIASA

Finally we apply quantified annual efficacy change rates for each of the five combinations of SSP and hydro-economic classification using a range of historically observed technological change rates (Flörke, et al., 2013).

Applied annual efficacy change rates

A	B	C	D	E
1.2%	1.1%	1%	0.6%	0.3%
highest			lowest	

3.4 Structural changes

Manufacturing sector

Structural changes in manufacturing water use intensities depend on the one hand on the overall structure of a country's economy. On the other hand the type of industry employed for earning GVA in the manufacturing sector determines amounts of water demand. For example in the U.S. the five most water-intensive non-agricultural or non-power generation industries include forest products (esp. pulp & paper), steel, petroleum, chemicals, and food processing. Other water intensive manufacturing sectors include textile production (for dyeing or bleaching) and semiconductor manufacturing. Structural changes also result from geographical shifts in production chains, e.g. installation of technologies from western countries in developing countries or Western countries sourcing out their industries.

The WFaS 'fast-track' does not consider assumptions for structural change in the manufacturing sector due to a lack of sector specific economic modeling consistent with SSP storylines. However, in some global water models (e.g. WaterGAP), manufacturing water use intensity is correlated with economic development, i.e. water use intensity is lower in countries with higher GDP per capita.

Electricity sector

The vast majority of water used in the energy sector is for cooling at thermal power plants, as water is the most effective medium for carrying away huge quantities of waste heat (IEA, 2012). Water withdrawals for cooling depend on fuel type and cooling technology. For example, nuclear power plants require larger water withdrawals per unit of electricity produced compared to fossil powered plants. Gas-fired power plants are the least water intensive. There are three basic types of cooling technology in use: once-through-cooling, recirculation (tower) cooling, and dry cooling. The latter is the least water intensive from both water withdrawal and consumption point of view but also the least energy efficient

(Koch & Vögele, 2009). By changing the cooling system of power plants from once-through systems to closed circuit systems, the vulnerability of power plants to water shortages can be reduced.

In general, a power plant's lifetime is about 35 to 40 years (Markewitz & Vögele, 2001). When economies have sufficient investment potential (i.e. in HE-2 and HE-3) or the societal paradigm strives for resource-efficient economies (as in SSP1) we assume an improved water use efficiency due to structural changes. In these scenarios, power plants are replaced after a service life of 40 years by plants with modern water-saving tower-cooled technologies. Such replacement policy is in line with the EU's policy on "Integrated Pollution Prevention and Control (IPPC)" (Commission, 2008). In addition all new power plants are assumed to have tower-cooling.

4. Domestic water use

Domestic water use includes water use for personal use, i.e. not for industrial production. The bulk of water consumed for indoor and outdoor private household purposes (e.g. drinking water, showers, laundry, swimming pool, irrigation of private gardens). In addition domestic water use includes municipal water use for public services (e.g. schools) and for small businesses. Main household water uses include drinking, preparing food, bathing, washing clothes and dishes, brushing your teeth, watering the yard and garden.

Worldwide domestic water use currently accounts for about 12% of total human water withdrawal (Flörke, et al., 2013). There is a huge regional variation ranging from less than 4% in some developing countries (e.g. Vietnam, Nepal) to over 90% in e.g. Ireland (AQUASTAT). The municipal water use per capita also varies greatly. In many developing countries municipal water use is less than 50 m³/capita/year. About a dozen of countries withdraw over 200 m³/capita/year including the United States, Canada, Australia, Singapore, and Qatar.

4.1 Water dimensions

4.1.1 Components of domestic water use

Components of domestic water use differ significantly between industrialized and developing regions. The main water use contributors in developed countries are toilet flushing, showering, laundry and outdoor water use. Smaller contributors are drinking water for consumption, cleaning (dishes, home, car, ...) and other.

Toilet flushing

The average frequency for the number of toilet flushes in Dutch homes is ca. 6 per person per day. A behaviour campaign (in case of water stress) may help to reduce the flushing

frequency or flushing amount but a hygiene culture may be difficult to alter. The volume per flush is 15 Litre for old toilets, 6 Litre with dual flush for new toilets. A development towards toilets that use more water is perceivable, e.g. one that uses water for extra cleaning after each flush. Toilets that use no (or very little water) are being developed, but so far only installed in pilot projects. The replacement of existing toilets will follow the replacement rate of homes or bathrooms, ca. 40 years (Foekema and van Thiel 2011).

Shower and bath

The use of a shower or bath or public bath for personal hygiene is determined by the availability of both the water supply (enough water, enough pressure, household connections) and the drinking water installation (availability of hot water). In poor countries where no shower is available now, the water use will increase when showers are becoming more common.

The showering and bathing frequency are determined by culture and climate. There are differences between neighboring countries. For example, in the UK bathing is popular, in the Netherlands people take a bath only once per two weeks on average. Behavior determines the showering duration. In the Netherlands, teenagers take much longer showers than elderly people.

Technology determines the flow rate (water saving shower head and type of water heater). More luxurious showers with a high flow rate are on the market and are being installed in richer countries. In countries where showers are available the installation of water saving shower heads takes ca. 20 years, when it reaches a ceiling. Note that at the same time the shower frequency has increased which lead to an increase in water use for the shower. The shower frequency is related to the average temperature (Foekema and van Thiel 2011).

Laundry

With a growing economy more people own a washing machine and wash their clothes more often. These increases will not be endless, but there will be a plateau value. The frequency of clothes washing with a washing machine is determined by behaviour and influenced by perception of what needs to be washed.

Technology determines the water volume used per washing cycle. For example, a top loader washing machine with a vertical axis uses much more water than a front loader machine with a horizontal axis (where only the bottom half of the machine is filled with water). The energy use of a washing machine is largely determined by the heating of the water; less water means less energy use. Energy conservation was a big driver for water conservation of washing machines. In Western Europe front loaders with energy label AAA (EU labelling) are most common. In the USA top loaders are still the most common. In Asia there are top loaders that do not heat the water. New technologies aim at using less soap and less warm water. However, new cleansing technologies may not require less water. The replacement of existing washing machines takes ca. 30 years (Foekema and van Thiel 2011).

Outdoor water use

Outdoor water use is used for watering the garden, swimming pools, washing the car, etc. Awareness may lead to using alternative sources (rain water, ground water, surface water)

or less water (no green grasses needed, re use water in a car wash). Hose pipe bans are known measures during dry periods.

4.1.2 Drivers for domestic water use

Access: As shown in Table 1 accessibility to water determines the extents of water use. Moreover when households have a simple way of heating their water (access to gas or electricity), they will use more hot water and thus will use more water. As access increases in developing countries, domestic water use will increase.

Penetration rate: When people have a washing machine at their home, they will use it more often. With an increasing number of people owning a water efficient washing machine, the total water consumption will decrease.

Volume per use & flow rate and duration: The total volume per water using event is determined either by the appliance (volume of cistern, intake of washing machine) or by the system + person who uses it (flow rate and duration of taking a shower).

Table 1. Domestic water consumption per person

Water source several kilometres away	2–4 litres per day
Water source up to 1 kilometre away	4–8 litres per day
Water next to the house	10–20 litres per day
Water in the home for toilet, tap and shower	60–100 litres per day
Water in the home for toilet, bath, kitchen and laundry	100–250 litres per day

Source: FAO, 2011: Rural structures in the tropics

Frequency of use: The frequency of use determines the total water use per day. The user himself influences this. Habits and culture play an important role.

Technology applied: Water volumes used for washing machines, toilets and outdoor water use depend on technology.

4.3 SSP storylines and implications for domestic water use

In the following we scrutinize each SSP narrative for developments relevant for water use in the domestic sector, and interpret those in terms of implications for domestic water use intensities.

SSP1: Sustainability – Taking the green road

Elements of the SSP storyline relevant for the DOMESTIC sector

- ✓ Inequality reduction across and within economies.

- ✓ Effective and persistent cooperation and collaboration across the local, national, regional and international scales and between public organizations, the private sector and civil society within and across all scales of governance.
- ✓ Resource use efficiency optimization associated with urbanizing lifestyles.
- ✓ Changing consumption and investment patterns.
- ✓ Civil society helps drives the transition from increased environmental degradation to improved management of the local environment and the global commons.
- ✓ Research and technology development reduce the challenges of access to safe water.
- ✓ Emphasis on promoting higher education levels, gender equality, access to health care and to safe water, and sanitation improvements.
- ✓ Investments in human capital and technology lead to a relatively low population.
- ✓ Better-educated populations and high overall standards of living confer resilience to societal and environmental changes with enhanced access to safe water, improved sanitation, and medical care.

Implications for domestic water use intensity

- ✓ Management of the global commons will slowly improve if cooperation and collaboration of local, national, and international organizations and institutions, the private sector, and civil society is enhanced.
- ✓ A demographic transition to lower population levels can be achieved if education and health investments are increased.
- ✓ Inequality can be reduced both across and within countries if development goals are achieved.
- ✓ Sustainability relies on increasing environmental awareness in societies around the world.
- ✓ Industrialized countries support developing countries in their development goals by providing access to human and financial resources and new technologies.

SSP2: Middle of the road

Elements of the SSP storyline relevant for the DOMESTIC sector

- ✓ Moderate awareness of the environmental consequences of choices when using natural resources.
- ✓ There is relatively weak coordination and cooperation among national and international institutions, the private sector, and civil society for addressing environmental concerns.
- ✓ Education investments are not high enough to rapidly slow population growth.
- ✓ Access to health care and safe water and improved sanitation in low-income countries makes unsteady progress.
- ✓ Gender equality and equity improve slowly.

- ✓ Consumption is oriented towards material growth, with growing consumption of animal products.
- ✓ Conflicts over environmental resources flare where and when there are high levels of food and/or water insecurity.
- ✓ Growing energy demand lead to continuing environmental degradation.

Implications for domestic water use intensity

- ✓ Weak environmental awareness trigger slow water security and progress in water use efficiencies.
- ✓ Global and national institutions lack of cooperation and collaboration make slow progress in achieving sustainable development goals.
- ✓ Growing population and intensity of resource leads to environmental systems degradation.
- ✓ Lower education investments do not promote slow population growth.
- ✓ Access to health care, safe water, and sanitation services are affected by population growth and heterogeneities within countries.
- ✓ Conflicts over natural resources access and corruption trigger the effectiveness of development policies.

SSP3: Regional Rivalry – A rocky road

Elements of the SSP storyline relevant for the DOMESTIC sector

- ✓ Societies are becoming more skeptical about globalization.
- ✓ Countries show a weak progress in achieving sustainable development goals.
- ✓ Environmental policies have a very little importance. Serious degradation of the environment becomes more important.
- ✓ Cooperation among organizations and institutions is weak. Their leadership is highly questionable.
- ✓ Low investments in education and in technology increases socioeconomic vulnerability.
- ✓ Growing population and limited access to health care, safe water and sanitation services challenge human and natural systems.
- ✓ Gender equality and equity remain stable.
- ✓ Consumption is material intensive and economic development remains stratified by socioeconomic inequalities.

Implications for domestic water use intensity

- ✓ Countries are pushed to focus on domestic issues.
- ✓ National and regional security issues foster stronger national policies to secure water resources access and sanitation services.
- ✓ Consumption is primarily material-intensive and water use important.
- ✓ A move towards sustainable development goals will lead to authoritarian forms of government and, consequently to a rise in social water awareness.

- ✓ Water security and environmental systems health is triggered by high levels of water consumption and limited development on human capital.
- ✓ National rivalries between the countries in a certain region weak progress toward development goals and increases competition for natural resources.

SSP4: Inequality – A road divided

Elements of the SSP storyline relevant for the DOMESTIC sector

- ✓ Inequalities between and within countries are driven by reduced technology development and higher education.
- ✓ Population has limited access to national institutions.
- ✓ Environmental awareness is limited. Very little attention is given to global environmental problems and their consequences for poorer social groups.
- ✓ Decision power is concentrated between certain nations and business.
- ✓ The most vulnerable groups have little representation. Lack of capacity to organize themselves challenges their opportunities to access natural resources, higher levels of education and water security.
- ✓ Economic opportunities are not generalized and many people have limited participation opportunities.
- ✓ Economic uncertainty leads to relatively low fertility and low population growth in industrialized countries.
- ✓ In low-income countries, large cohorts of young people result from high fertility rates.
- ✓ Lack of access to health translates into high levels of mortality.
- ✓ People rely on local resources when technology diffusion is uneven.
- ✓ Socioeconomic inequities trigger governance capacity and challenge progress towards sustainable goals.
- ✓ Agriculture is dominated by industrialized agriculture and monoculture production.
- ✓ Food trade is global, but access to market is limited.
- ✓ Challenges to land use management and to adapt to environmental degradation are high.

Implications for domestic water use intensity

- ✓ A move towards more domestic water intensive use will lead to a rise in water consumption and use of local resources.
- ✓ New technologies and technical progress will have an impact on water coverage and water sanitation services.
- ✓ Increasing equality in access to education will favor substantial population participation in economic activities.
- ✓ Environmental awareness will be more important if educational gaps are reduced.
- ✓ Access to effective institutions will foster social adaptation and it will reduce environmental stress.

SSP5: Fossil-fueled development—Taking the highway

Elements of the SSP storyline relevant for the DOMESTIC sector

- ✓ Global economic growth promotes robust growth in demand for services and goods.
- ✓ Developing countries aim to follow the fossil- and resource-intensive development model of the industrialized countries.
- ✓ Rise in global institutions and global coordination.
- ✓ Competitive markets and more effective institutions lead to lower levels of corruption and strong rule of law.
- ✓ Social cohesion and gender equality are strengthened, and consequently social conflicts are decreased.
- ✓ More important economic cooperation.
- ✓ Higher education and better health care accelerate human capital development, and decline fertility levels.
- ✓ Investments in technological innovation are very high leading to increasing labor productivity, fossil energy supply, and managing the natural environment.

Implications for domestic water use intensity

- ✓ Accelerated globalization and rapid development are based on exploitation of fossil fuel resources and the adoption of resources and energy intensive lifestyles.
- ✓ Social international mobility increases because of labor markets opening.
- ✓ Industrialization is driven by high energy demand and engineered infrastructure.
- ✓ Higher demand for services and goods promote an increase use of fossil resources.
- ✓ Urbanization leads to more structural investments in technology innovation.
- ✓ Technological progress translates into strong resilience on fossil fuels and lower environmental concerns.

4.3 Qualitative and quantitative scenario assumptions

4.3.1 Technological change rates

Technology influences the volume of water required for specific domestic uses (e.g. toilet, washing machine, dishwasher, shower). Water use intensities decrease with the availability and speed of introduction of new technologies.

Technological change is an integral part of the economy of a country or region. The legal, institutional, education and financial systems determine the potential for innovation and their implementation. Against this background we argue that the interpretation of technological change in the context of SSPs and position of individual countries in hydro-economic classes is similar in the industry and domestic sector. Therefore the qualitative and quantitative scenario assumptions specified in section 2.3 are also valid for the domestic sector. This approach is compatible with global water use models, which apply similar technological change rates for the industry and domestic sector.

4.3.2 Structural changes: Access and Behavior

Structural changes in the domestic sector refer to the number of people having access to water sources and behavior. Only in SSP1 (Sustainability Scenario), we assume by 2050 a 20% reduction in domestic water use intensity due to behavioral changes. The WFaS ‘fast-track’ applied global water use models calculate domestic water use at the national level where access to safe drinking water is not considered.

5. Agricultural water use

At the global level, agriculture is by far the largest user of water accounting for about 70% of the total human water withdrawals. In many developing countries agriculture accounts for over 90% of total water use. The vast majority of water use in agriculture is for irrigation. In addition some water use is for raising livestock herds in intensive production systems (feedlots and finishing systems). Although water uses for direct animal watering (cooling) and drinking are small, they are rapidly growing and of importance in selected countries (e.g. Australia, Botswana).

5.1 Water dimensions related to agricultural production

There are various important water dimensions/elements related to agricultural production, crop productivity and resource use. Of particular interest here are the variables associated with irrigation development, which have been subdivided into four dimensions:

- 1) Irrigation cropping intensity:** indicates the multiple use of irrigated land within one year; it is defined as the ratio of [harvested irrigated crop area] to [actually irrigated land equipped with irrigation].

Cropping intensity on irrigated land generally depends on several factors: (i) the thermal regime of a location, which determines how many days are available for crop growth and how many crops in sequence can possibly be cultivated; (ii) irrigation water availability and reliability of water supply; and (iii) sufficient availability of inputs, agricultural labor and/or mechanization. In case of terrain limitations for mechanization and labor shortages, e.g. due to employment outside agriculture and/or low population growth, such economic reasons may not allow to realize the climatic potential (e.g., such as has been happening in some eastern provinces of China where multi-cropping factors have been decreasing in recent years). In general, however, future changes in irrigation intensity will tend to increase with warming in temperate zones, but may be limited or even decrease where seasonal water availability is a major constraint.

- 2) Utilization intensity of irrigated land:** is given by the ratio of [actually irrigated land] to [land equipped with irrigation].

There are (at least) four factors that may affect actual utilization of areas equipped for irrigation. First, in a context of increased competitiveness (e.g. due to sector liberalization) and possibly shrinking land intensity, actually irrigated areas may

decrease more than the area equipped for irrigation. Second, in a context where additional areas are equipped for irrigation to reduce drought risk, i.e. as a safeguard against ‘bad’ years, the effect could be an increase of area equipped for irrigation but an overall reduction of utilization of these areas, because such areas would not be irrigated every year. Third, when water availability deteriorates (or cost of irrigation/groundwater increases), farmers may be forced to reduce utilization of areas equipped for irrigation. Fourth, it is conceivable that under poor economic conditions and incentives some areas equipped for irrigation are not well maintained and may become unusable.

- 3) Irrigation efficiency:** measures the effectiveness of an irrigation system in terms of the ratio of [crop irrigation water requirements] over [irrigation water withdrawals].

Overall irrigation efficiency is a function of the type of irrigation used and the technology being used within each type. Future changes will largely depend on investments being made to shift to more efficient irrigation types and to updating each type’s technology to state-of-the-art, and to some extent will depend on crop type (for instance, paddy rice needs flood irrigation, for some crops sprinkler cannot be used, for some drip irrigation may be too expensive) and possibly new cultivation practices. Therefore, judging about future irrigation efficiency requires an inventory/estimation of the status quo (current distribution by type of irrigation and crops irrigated) and a projection of future irrigation systems and related technology assumptions.

- 4) Area equipped for irrigation:** Area equipped to provide water (via irrigation) to crops. It includes areas equipped for full/partial control irrigation, equipped lowland areas, and areas equipped for spate irrigation.

Changes in a country’s area equipped for irrigation will depend on several economic, technological and political factors, which determine the need, economic profitability and biophysical viability of irrigation expansion. Key factors included among these are: (i) availability, reliability and access to water; (ii) irrigation impact (yield increase and/or reduced variability); (iii) growth of demand for agricultural produce due to demographic and economic changes; (iv) availability of resources with rain-fed potential for conversion to agriculture (where available, these might be preferable and cheaper to develop rather than expanding irrigation); (v) existing current yield gaps in rain-fed and/or irrigated land; (vi) cost of irrigation; (vii) profitability and economic means available to invest in irrigation; (viii) state food security and self-reliance policies.

5.2 SSP storylines and implications for agricultural water use

Here we provide a brief summary of the salient features that characterize different shared socio-economic development pathways (SSPs) and we indicate some direct and indirect consequences this may have for the agricultural sector and associated irrigation water use.

SSP1: Sustainability – Taking the green road

In SSP1 the world is gradually moving toward sustainability.

- ✓ Sustainability concerns; more stringent environmental regulation implemented
- ✓ Rapid technological change
- ✓ Energy efficiency and improved resource efficiency
- ✓ Relatively low population growth; emphasis on education
- ✓ Effective institutions
- ✓ Wide access to safe water
- ✓ Emphasis on regional production
- ✓ Some liberalization of agricultural markets
- ✓ Risk reduction and sharing mechanisms in place

The above general tendencies of development in the SSP1 World can be interpreted to have the following agriculture/irrigation related implications:

- ✓ Improved agricultural productivity and resource use efficiency
- ✓ Quite rapid reduction of prevailing yield gaps toward environmentally sustainable and advanced technology yield levels
- ✓ Improving nutrition with environmentally benign diets with lower per capita consumption of livestock products
- ✓ Enforced limits to groundwater over-exploitation
- ✓ Large improvements of irrigation water use efficiency
- ✓ Reliable water infrastructure and water sources
- ✓ Enhanced treatment and reuse of water
- ✓ Concern for pollution reduction and water quality, implying widespread application of precision farming and nutrient management
- ✓ Risk management and related measures implemented to reduce and spread yield risks

SSP2: Middle of the road

In SSP2 the world is the world is progressing along past trends and paradigms.

- ✓ Most economies are politically stable
- ✓ Markets are globally connected but function imperfectly
- ✓ Slow progress in achieving development goals of education, safe water, health care
- ✓ Technological progress but no major breakthrough
- ✓ Modest decline in resource use intensity
- ✓ Population growth levels off in second half of century
- ✓ Urbanization proceeds according to historical trends
- ✓ Consumption is oriented towards material growth
- ✓ Environmental systems experience degradation
- ✓ Significant heterogeneities exist within and across countries
- ✓ Food and water insecurity remain in areas of low-income countries
- ✓ Barriers to enter agricultural markets are reduced only slowly
- ✓ Moderate corruption slows effectiveness of development policies

The SSP2 World is characterized by dynamics similar to historical developments. This would imply continuation of agricultural growth paths and policies, continued protection of national agricultural sectors, and further environmental damages caused by agriculture:

- ✓ Modest progress of agricultural productivity
- ✓ Slow reduction of yield gaps especially in low-income countries
- ✓ Increasing per capita consumption of livestock products with growing incomes
- ✓ Persistent barriers and distortions in international trade of agricultural products
- ✓ No effective halt to groundwater over-exploitation
- ✓ Some improvements of water use efficiency, but only limited advances in low-income countries
- ✓ Some reduction of food insecurity due to trickle down of economic development
- ✓ Food and water insecurity remain as problems in some areas of low-income countries
- ✓ No effective measures to prevent pollution and degradation by agricultural practices; environmental risks caused by intensive application of fertilizers and agro-chemicals, and intensive and concentrated livestock production systems
- ✓ Only moderate success in reducing climate risks and vulnerability

SSP3: Regional rivalry

In SSP3 the world development is stagnating.

- ✓ Growing concerns about globalization and focus on national/regional issues and interests
- ✓ Markets (agriculture, energy) are protected and highly regulated
- ✓ Global governance and institutions are weak
- ✓ Low priority for addressing environmental problems
- ✓ Slow economic growth
- ✓ Low investment in education and technology development
- ✓ Poor progress in achieving development goals of education, safe water, health care
- ✓ Increase in resource use intensity
- ✓ Population growth low in developed, high in developing countries; overall large increase
- ✓ Urbanization proceeds slowly; disadvantaged continue to move to unplanned settlements
- ✓ Serious degradation of environmental systems in some regions
- ✓ Large disparities within and across countries
- ✓ Weak institutions contribute to slow development

Development in the SSP3 World will lead to manifold problems in food and agriculture, with implications for irrigation development and water challenges, characterized by:

- ✓ Poor progress with agricultural productivity improvements in low-income countries due to lack of investment and education
- ✓ Widespread lack of sufficient investment and capacity for yield gap reduction in developing countries
- ✓ Growing protection of national agricultural sectors and increasing agricultural trade barriers

- ✓ Low priority to halt environmental degradation caused by agriculture (erosion, deforestation, poor nutrient management, water pollution and exploitation)
- ✓ Widespread pollution and deterioration of ecosystems
- ✓ Continued deforestation of tropical rain-forests
- ✓ Only modest improvements of irrigation water use efficiency
- ✓ Persistent over-exploitation of groundwater aquifers
- ✓ Widespread lack of access to safe water and sanitation
- ✓ Unreliable water and energy supply for agricultural producers
- ✓ Food and water insecurity persist as major problems in low-income countries
- ✓ High population growth and insufficient development leave behind highly vulnerable human and environmental systems

SSP4: Inequality – A road divided

In SSP4 inequalities and fragmentation is increasing.

- ✓ Inequalities within and between countries increase; fragmentation increases
- ✓ Wealth and income increasingly concentrate at the top
- ✓ Global governance and institutions are weak
- ✓ Public expenditures focus on and benefit a small, highly educated elite
- ✓ Polarization creates a mixed world with income inequality increasing
- ✓ Political and economic power becomes more concentrated in a small political and business elite
- ✓ Increasing price volatility in biomass and energy markets
- ✓ Well-educated elite induces technical progress and efficiency improvements
- ✓ A world that works well for the elite but where development stagnates or decreases opportunities for those left behind
- ✓ Low fertility in developed countries. High fertility and high urbanization in low and middle income countries.
- ✓ Large disparities of incomes and well-being within and across countries
- ✓ Poor access to institutions by the poor
- ✓ No adequate protection for those losing out in development; these groups lose assets and livelihoods

Development in the SSP4 World creates a polarization and unequal societies with small and well-educated elites and a large share of poor and under-privileged citizens. For agriculture/irrigation use this may imply:

- ✓ In part, a trend towards large, technologically advanced and profitable farms. Yet, at the same time also poor progress of agricultural productivity in low-income farm households due to lack of investment and education
- ✓ Land and water grabbing to the benefit of elites and large international agro-complexes
- ✓ Efficient irrigation systems used for profitable and internationally traded cash crops. Little improvements in irrigation efficiencies of the low income farm sector
- ✓ In low-income countries, food and water insecurity persist as major problems outside the privileged elites
- ✓ High population growth in developing countries and polarizing development leave behind highly vulnerable rural systems

- ✓ No adequate protection for those losing out in development; these groups lose assets and livelihoods
- ✓ Co-existence of well-organized agricultural production and marketing chains, run by the elite, and wide-spread subsistence and landless dwellers in rural areas

SSP5: Fossil-fueled development

In the SSP5 World is living the “development first” paradigm

- ✓ World is developing rapidly, powered by cheap fossil energy
- ✓ Economic success of emerging economies leads to convergence of incomes
- ✓ Decline of income inequality within regions
- ✓ World views oriented towards market solutions
- ✓ Developing countries follow the development model of the industrial countries
- ✓ Rapid rise in global institutions
- ✓ Strong rule of law; lower levels of corruption
- ✓ Accelerated globalization and high levels of international trade
- ✓ Policies emphasizing education and health
- ✓ Consumerism, resource-intensive status consumption, preference for individual mobility
- ✓ Population peaks and declines in 21st century
- ✓ Strong reduction of extreme poverty
- ✓ Very high global GDP; continued large role of manufacturing sector
- ✓ All regions urbanize rapidly
- ✓ Widespread technology optimism; high investments in technological innovations
- ✓ Local environmental problems addressed effectively; however, lack of global environmental concern and solutions

Development in the SSP5 World is rapid and based on consumerism, fossil energy, and fast technological progress. World views and policies are following an “economics and development first” paradigm:

- ✓ Agro-ecosystems become more and more managed in all world regions
- ✓ Large increases in agricultural productivity; diffusion of resource-intensive management practices in agriculture
- ✓ Large improvements of irrigation water use efficiency
- ✓ Enhanced treatment and reuse of water
- ✓ High per capita food consumption and meat-rich diets globally
- ✓ Land and environmental systems are highly managed across the world
- ✓ Large reduction of agricultural sector support measures
- ✓ Global agricultural markets are increasingly integrated and competitive
- ✓ Improved accessibility due to highly engineered infrastructures
- ✓ Large-scale engineering of water infrastructure to manage and provide reliable water supply
- ✓ Economic use of land is given priority over nature protection and sustainability of ecosystems

5.3 Qualitative scenario assumptions

After summarizing the main characteristics and storyline features of each SSP and interpret their relevance and implication for agricultural production conditions and irrigated agriculture, we go into a qualitative rating of scenario specific agricultural/irrigation water dimensions.

5.3.1 Irrigation cropping intensity

As pointed out, changes in cropping intensity on irrigated land – i.e. multiple use of the land within one year (ideally measured as irrigated cropping days per year) – critically depends on changes in the thermal (and possibly precipitation) regime of a location. Water shortage, high economic costs of irrigation and shortage of labor/mechanization could mean that farmers are not able or do not want to exploit longer thermal growing seasons (under climate change). Such socio-economic and demographic limitations are more likely to occur in SSP 1 and SSP 5. According to our definition of hydro-economic classes, physical and economic water scarcity may limit cropping intensity in the countries of H-E 3 and H-E 4.

Water Dimension – Irrigation Cropping Intensity Assumptions

	SSP/Class		HE-1	HE-2	HE-3	HE-4
			T	T	WL	WL
Irrigation Cropping Intensity (harv ha/irrig ha)	SSP 1	EL	EL-T	EL-T	EL-WL	EL-WL
	SSP 2	T	T	T	T-WL	T-WL
	SSP 3	T	T	T	T-WL	T-WL
	SSP 4	T	T	EL-T	T-WL	T-WL
	SSP 5	EL	EL-T	EL-T	EL-WL	EL-WL

Source: WFaS, IIASA

In the water dimensions table for ‘Irrigated cropping intensity’ the symbol ‘T’ is used to indicate ‘according to thermal regime trend’, ‘EL’ to indicate below-potential intensities due to demographic/economic limitations, and ‘WL’ to mean intensities will be below the thermal potential due to water limitations.

In sector-specific or comprehensive integrated assessment modeling where all relevant explanatory factors are simulated, the rationale reflected in the assumptions table can be incorporated in the simulated cropping and land use decisions. For modeling and exploratory assessments, where such detail is not possible, the assumptions table can be condensed into a simple rating table, as given below.

In this table, an ‘A’ rating is used to indicate increase of irrigation cropping intensity when warming occurs; note, this will still depend on broad climatic characteristics, e.g. by thermal climate zones (tropics = no increase due to warming; sub-tropics = very modest increase; temperate zone = significant lengthening of growing season and increase of multi-cropping with temperature).

Water Dimension – Irrigation Cropping Intensity Rating

	SSP/Class		HE-1	HE-2	HE-3	HE-4
			T	T	WL	WL
	SSP 1	EL	B	B	C	C

Irrigation Cropping Intensity (harv ha/irrig ha)	SSP 2	T	A	A	B	B
	SSP 3	T	A	A	B	B
	SSP 4	T	A	B	B	B
	SSP 5	EL	B	B	C	C

Source: WFaS, IIASA

5.3.2 Utilization intensity of area equipped for irrigation

Changes in the actual utilization of ‘areas equipped for irrigation’ will as well depend on a mixture of agronomic and economic factors including biophysical changes, costs and profitability, risk mitigation objectives, and capital constraints in rehabilitation and maintenance. It is worth noting that FAO estimates a 40-year average life time of an irrigation system, which implies that on average 2.5% of the area equipped has to be rehabilitated/re-equipped each year. There is only some empirical information available, estimates of areas actually irrigated are incomplete and only point estimates but no time-series exist. Therefore, the assumptions table concerning the utilization intensity of areas equipped for irrigation is somewhat speculative and will benefit from inputs by sector stakeholders.

Water Dimension – Irrigation Utilization Intensity Assumptions

		SSP/Class		HE-1	HE-2	HE-3	HE-4
				T	R	R	T
Irrigation Utilization Intensity (irrig ha/equ. ha)	SSP 1	R	R-T	R	R	R	R-T
	SSP 2	T	T	T	T-R	T	T
	SSP 3	R/T	R-T	T-R	T-R	R-T	R-T
	SSP 4	R	R-T	R	R	R-T	R-T
	SSP 5	T	T	T-R	T-R	T	T

Source: WFaS, IIASA

Our assumption concerning different hydro-economic classes is that utilization of irrigation systems in economically rich countries (HE-2 and HE-3) could decrease (as indicated by ‘R’) due to the fact that areas may increasingly be equipped to reduce drought risks, stabilize production and buffer against possible increasing variability. Across SSPs, we consider conditions and objectives in development path SSP 1 and SSP 4 to possibly lead to reduced utilization rates. A simplified rating table is presented below where the ‘C’ rating indicates a tendency toward lowering utilization rates whereas an ‘A’ rating suggests maintaining or even increasing utilization rates of equipped areas.

Water Dimension – Irrigation Utilization Intensity Rating

		SSP/Class		HE-1	HE-2	HE-3	HE-4
				T	R	R	T
Irrigation Utilization Intensity (irrig ha/equ. ha)	SSP 1	R	B	C	C	B	B
	SSP 2	T	A	A	B	A	A
	SSP 3	R/T	B	B	B	B	B
	SSP 4	R	B	C	C	B	B
	SSP 5	T	A	B	B	A	A

Source: WFaS, IIASA

5.3.3 Irrigation water use efficiency

Overall irrigation water use efficiency is a function of the type of irrigation system being used and the specific technology available within each type. Future changes will largely depend on investments being made to shift to more efficient irrigation types and to updating each type’s technology to state-of-the-art, and to some extent will depend on crop type (for instance, paddy rice needs flood irrigation and additional irrigation water for cultivation; for some crops sprinkler cannot be used; for some drip irrigation may be too expensive). In the assumptions table, the symbol ‘H’ indicates higher economic capacity (compared to trend) to improve irrigation efficiency, and when used across hydro-economic classes means high incentive to improve water use efficiency due to water scarcity and hydrological complexity. The symbols ‘M’ and ‘L’ indicate respectively ‘average/moderate’ and ‘low’ capability or incentives.

As a general principal, we are assuming that: (i) high hydrological complexity will tend to induce improvements in irrigation water use efficiency; (ii) high economic growth and income per capita will allow fast improvements of irrigation efficiency; and (iii) low income, inefficient institutions and low hydrological complexity will combine to result in little or no improvement of irrigation water use efficiency.

Water Dimension – Irrigation Water Use Efficiency Assumptions

			HE-1	HE-2	HE-3	HE-4
			L	M	H	H
Irrigation Utilization Intensity (irrig ha/equ. ha)	SSP 1	H	H-L	H-M	H	H
	SSP 2	M	M-L	M	M-H	M-H
	SSP 3	L	L	L-M	L-H	L-H
	SSP 4	M	M-L	M	M-H	M-H
	SSP 5	H	H-L	H-M	H	H

Source: WFaS, IIASA

The above table has been simplified into a rating table using five classes, rated ‘A’ to ‘E’, which reflect the combination of economic capacity and magnitude of water challenges that can be derived from the scenario narratives and hydro-economic classification. The ‘A’ rating is used for the combination of high economic capability, high priority and high urgency to increase water use efficiency due to limited water availability. On the opposite side of the rating scale, the ‘E’ rating signals that neither the economic means nor the urgency exist to prioritize and allow investments in irrigation water use efficiency. Hence, we expect that the strongest incentives and support to move toward the technically possible will exist in SSP 1 and SSP 5 and particularly so in water-scarce countries in HE-3 and HE-4.

Water Dimension – Irrigation Water Use Efficiency Rating

			HE-1	HE-2	HE-3	HE-4
			L	M	H	H
Irrigation Utilization	SSP 1	H	C	B	A	A
	SSP 2	M	D	C	B	B

Intensity (irrig ha/equ. ha)	SSP 3	L	E	D	C	C
	SSP 4	M	D	C	B	B
	SSP 5	H	C	B	A	A

Source: WFaS, IIASA

5.3.4 Area equipped for irrigation

In the past, the area equipped for irrigation has been continuously expanding (from 142 million ha in 1961/63 to 302 million ha in 2005/07) although more recently this expansion has slowed down (Alexandratos & Bruinsma, 2012).

Irrigated agriculture has been critically important for the growth of production during the last 50 years. In 2000, area equipped for irrigation accounted for some 18 percent of total cultivated land and for more than 40 percent of crop production (Fischer et al., 2012). Yet, for a number of reasons, FAO experts expect a sharp slowdown in the growth of areas equipped for irrigation as compared to the historical trend, reflecting the projected slower growth rate of future crop demand and production (due to slow-down of population growth), increasing scarcity of suitable areas for irrigation, as well as the scarcity of water resources in some countries, the rising cost of irrigation investment, and competition for water with other sectors.

Water Dimension – Assumptions regarding expansion of area equipped for irrigation

		SSP/Class		HE-1	HE-2	HE-3	HE-4
				M	L	L	M
Area Equipped for Irrigation	SSP 1	L	L-M	L	L	L	L-M
	SSP 2	M	M	M-L	M-L	M-L	M
	SSP 3	H	H-M	H-L	H-L	H-L	H-M
	SSP 4	M	M	M-L	M-L	M-L	M
	SSP 5	L	L-M	L	L	L	L-M

Source: WFaS, IIASA

For these reasons, the reference projection of FAO assumes that aggregate irrigated areas in developed countries will remain approximately stable (at about 70 million ha), whereas a net expansion by nearly 20 million ha would be achieved in developing countries, to 253 million ha in 2050. The expansion of irrigation is expected to be strongest (in absolute terms) in the more land-scarce regions, which will be hard-pressed to raise crop production through more intensive cultivation practices (Alexandratos & Bruinsma, 2012)

As shown in the assumptions table above, we conclude that incentives to increase the area equipped for irrigation will be low in scenarios with high technical progress and low population growth, such as SSP 1 and SSP 5, will be relatively high under SSP 3, and will

be moderate under SSP 2 and SSP 4. When looking across countries in different hydro-economic classes, incentives for expansion will be moderate in developing countries of HE-1 and HE-4, but for demographic and economic reasons only low in countries of HE-2 and HE-3.

For practical use, the above table can be simplified into a rating table using four classes, rated ‘A’ to ‘D’, which reflect the combination of demand growth, land abundance and magnitude of water challenges that can be derived from the scenario narratives and hydro-economic classification. While a ‘D’ rating signals modest decline (or at best stagnation) of areas equipped for irrigation, the ‘A’ rating indicates conditions under which the area equipped for irrigation can be expected to increase. Hence, we expect that the strongest incentives and need to expand the irrigated areas will exist in developing countries under SSP 3, the least in developed countries (HE-2 and HE-3) especially under SSP 1 and SSP 5.

Water Dimension – Rating the growth of area equipped for irrigation

			HE-1	HE-2	HE-3	HE-4
SSP/Class			M	L	L	M
Area Equipped for Irrigation	SSP 1	L	C	D	D	C
	SSP 2	M	B	C	C	B
	SSP 3	H	A	B	B	A
	SSP 4	M	B	C	C	B
	SSP 5	L	C	D	D	C

Source: WFaS, IIASA

It should be noted that the above rating table can provide general guidance only. In a country’s reality, several and diverse factors will determine the future expansion of land equipped for irrigation: (1) water availability and reliability, and cost of access; (2) availability of suitable land resources for conversion to rain-fed agriculture (as an alternative to irrigated cropping); (3) prevailing yield gaps; (4) demand growth for food and non-food biomass, and population growth; (5) state security and food self-reliance policies; (6) economic wealth.

6. Preliminary results of the WFaS 'fast-track' assessment

For the quantification of global scenarios of future water demand an ensemble of three global water models was used: H08 (Hanasaki, et al., 2008) (Hanasaki, et al., 2008), PCR-GLOBWB (Wada, et al., 2011) (Wada, et al., 2011) (Wada, et al., 2014), and WaterGAP (Döll, et al., 2003) (Döll, et al., 2012) (Flörke, et al., 2013).

Note that due to the fact that new SSP scenarios of future land use changes are still being developed for agricultural sector, we have not yet included irrigation and livestock sector in this ‘fast-track’ analysis. For a comprehensive assessment of future irrigation under the

latest RCP scenarios, we refer to (Wada, et al., 2013) who used a set of seven global water models to quantify the impact of projected global climate change on irrigation water demand by the end of this century, and to assess the resulting uncertainties arising from both the global water models and climate projections.

In addition, due to limited data available for future ecosystem service, we did not include the assessment of environmental flow requirements. We refer to (Pastor, et al., 2014) for a comprehensive assessment of global environmental flow requirements. Thus, here we primarily focus on the industrial (electricity and manufacturing) and domestic sectors.

6.1 Summary of drivers and assumptions

We simulate the characteristic macro-scale behavior of water demand per sector, based on various input data and associated scenario assumptions described in the former sections and summarized in Table 2 and 3. Critical water dimensions were evaluated qualitatively and quantitatively for each SSP and Hydro-Economic class. In the WFaS ‘fast-track’ analysis we’ve selected three SSP based scenarios for the quantification of spatially explicit global water use until 2050.

Table 2. Drivers and assumptions applied in the WFaS ‘fast-track’ scenario runs, deployed at country level

<i>Scenario</i>	SUQ (Sustainability Quest)	BAU (Business as usual)	DIV (Divided world)
Based on SSP	SSP1	SSP2	SSP3
Socio-Economics			
Population	SSP1 (IIASA-VIC v9)	SSP2 (IIASA-VIC v9)	SSP3 (IIASA-VIC v9)
Urban population	SSP1 (NCAR)	SSP2 (NCAR)	SSP3 (NCAR)
GDP	SSP1 (OECD ¹ v9)	SSP2 (OECD v9)	SSP3 (OECD v9)
Value added in Manufacturing ²	SSP1 & UNEP-GEO4 “Sustainability First”	SSP2 & UNEP-GEO4 “Markets First”	SSP3 & UNEP-GEO4 “Security First”
Energy consumption (KTOE)	MESSAGE ³	MESSAGE ³	MESSAGE ³
Electricity production (GWh)	Derived from MESSAGE	Derived from MESSAGE	Derived from MESSAGE
Technological & structural changes	Assumptions for technologic changes interpret the respective SSP narrative, differentiated by a country’s socio-economic ability to cope with water-related risks and its exposure to hydrologic challenges. The latter was achieved by grouping countries into “hydro-economic classes” (assumption details in Table 3)		

1 OECD Env-Growth Model; **2** only required for WaterGAP. The share of manufacturing gross value added in total GDP is taken from the UNEP GEO4 Driver Scenarios distributed by International Futures (pardee.du.edu); **3** Preliminary results (October 2013) from IIASA – MESSAGE-MACRO (Messner & Strubegger, 1995) (Rao & Riahi, 2006) model consistent with population and GDP projections for each SSP. The MESSAGE model (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) generated results for 23 regions, which were disaggregated to country level using the same distribution as in the year 2000 .

Table 3. Scenario assumptions for technology and structural change in the industry and domestic sector

Hydro-Economic (HE) classification*					
		HE-1	HE-2	HE-3	HE-4
Socio-economic capacity to cope with water-related risks					
		Low (poor)	High (rich)	High (rich)	Low (poor)
Exposure to hydrologic complexity & challenges					
		Low	Low	High	High
ENERGY SECTOR					
Technological change [annual increase]	SSP1	1.1 %	1.1 %	1.2 %	1.1 %
	SSP2	0.6 %	1.0 %	1.1 %	1.0 %
	SSP3	0.3 %	0.6 %	1.0 %	0.6 %
Structural change	SSP1	40 y	40 y	40 y	40 y
	SSP2	None	40 y	40 y	40 y
	SSP3	None	None	40 y	None

MANUFACTURING SECTOR					
Technological change [annual increase]	SSP1	1.1 %	1.1 %	1.2 %	1.1 %
	SSP2	0.6 %	1.0 %	1.1 %	1.0 %
	SSP3	0.3 %	0.6 %	1.0 %	0.6 %
DOMESTIC SECTOR					
Technological change [annual increase]	SSP1	1.1%	1.1 %	1.2 %	1.1 %
	SSP2	0.6%	1.0 %	1.1 %	1.0 %
	SSP3	0.3%	0.6 %	1.0 %	0.6 %
Structural change	SSP1	20% by 2050	20% by 2050	20% by 2050	20% by 2050
	SSP2	None	None	None	None
	SSP3	None	None	None	None

* The hydro-economic classification calculates for each country a compound indicator (values 0-1) for socioeconomic capacity to cope with water-related risks (economic-institutional capacity) and their exposure to hydrologic challenges and complexity (hydrological complexity). In this way each country was located in a two-dimensional space and grouped into four hydro-economic classes termed HE-1 to HE-4.

6.2 Industrial water use sector

All three models calculate both water withdrawal and water consumption, the latter subtracting the return flow to the rivers and groundwater. Industrial water use is generally calculated for individual countries with subsequent downscaling to a 0.5 degree by 0.5 degree longitude-latitude grid. While H08 downscaling is according to population distributions, PCR-GLOBWB and WaterGAP downscale to urban areas only.

A major difference among the employed water models relates to the sector details of the industry sector. H08 and PCR-GLOBWB determine water use for an aggregate industry sector. H08 calculates water use from total electricity production, while PCR-GLOBWB use GDP, total electricity production, and total energy consumption. In contrast WaterGAP separates water use for thermal electricity production and the manufacturing industry. This requires two additional input variables, thermal electricity production and manufacturing value added. Although estimates for those variables are consistent with H08 and PCR-GLOBWB input data (see Table 2 and 3), the results of WaterGAP simulation can differ substantially. This is particularly true for regions where thermal electricity production or manufacturing value added have a large share in the industrial water use compared to those of the other two models.

Ensemble results of global industrial water withdrawal highlight a steep increase in almost all SSP scenarios (Figure 4).

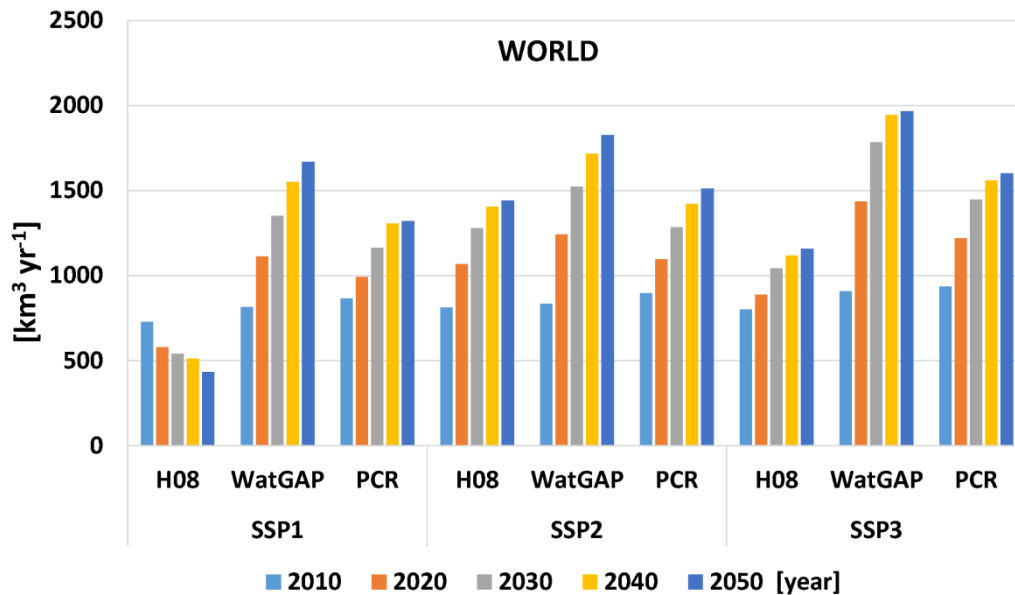


Figure 4. Ensemble of three global industrial water withdrawal (water demand) projections calculated with the global water models: H08, WaterGAP, and PCR-GLOBWB (PCR) for the years 2010, 2020, 2030, 2040, and 2050 respectively under three SSPs scenarios (SSP1, SSP2, and SSP3).

Global amounts reach nearly 2000 km³ yr⁻¹ by 2050, more than doubled compared to the present industrial water use intensity (850 km³ yr⁻¹). One major difference is a change in sign in SSP1 where H08 projects a downward trend by about 40% compared to PCR-GLOBWB and WaterGAP, which project about 50% and 100% increase respectively.

Under the SSP2 and SSP3 scenarios, the results are more consistent. Global industrial water withdrawals are projected to increase by 70-120% under the ‘business-as-usual’ SSP2 scenario and by 45-120% under the ‘Divided world’ SSP3 scenario. H08 has the largest range among the SSP projections between -40% decrease (SSP1) and 80% increase (SSP3). PCR-GLOBWB has relatively a narrow range between 50% increase (SSP1) and 70% increase (SSP3) and the range is even narrower for WaterGAP with 105% increase (SSP1) and 119% increase (SSP2). By 2050 WaterGAP projects the largest increase under SSP2, while the other models project that under SSP3.

Figure 5 shows global maps of projected domestic water withdrawals calculated from the ensemble of three water models. The projected trends and variability among the models are rather similar under the three SSP scenarios. We therefore show only the projections under the SSP2 scenario and refer to Annex II for the other projections under the SSP1 and SSP3 scenarios.

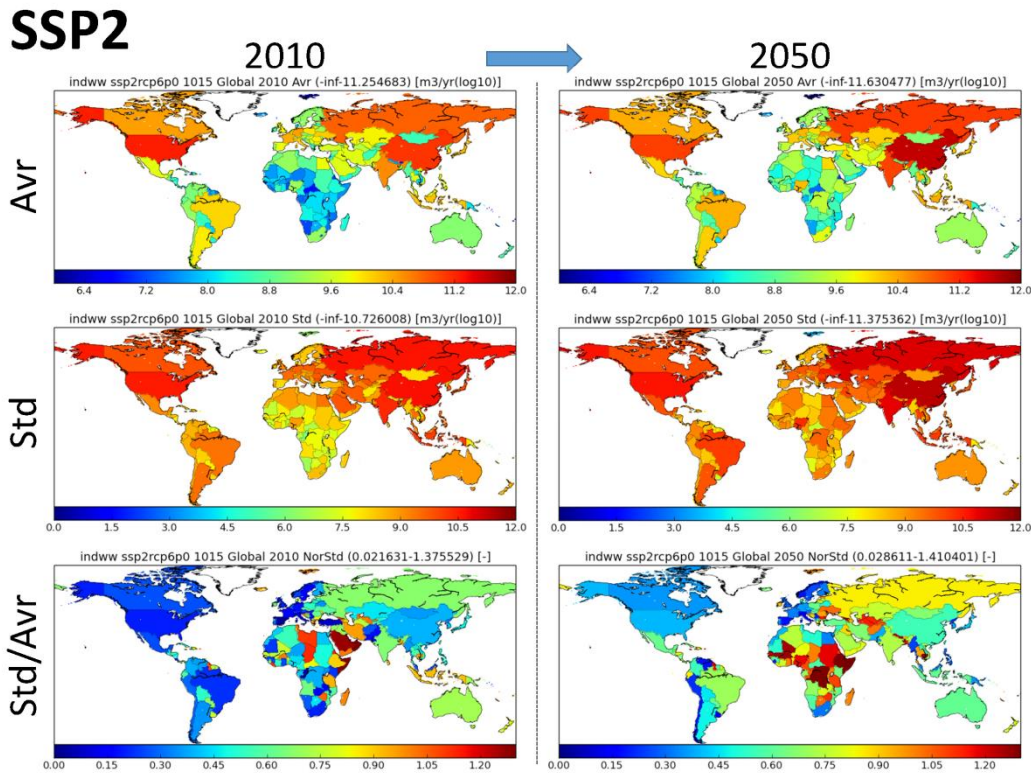


Figure 5. Ensemble statistics of three global water models for industrial water withdrawals (water demand), for 2010 and 2050, SSP2 scenario. *Avr* (Average), *Std* (Standard deviation), and *Std/Avr* denotes the coefficient of variations (CV).

The model agreement for the industry sector is already under the current conditions in many countries low ($CV > 0.5$). By 2050, the spread across the models becomes even wider for many countries in Asia, Africa, and South America ($CV > 0.75$). For both the industrial and domestic sector, the model agreement is particularly high for countries in North America (e.g., the USA), Western Europe (e.g., Germany), and Japan both for present condition as well as the future projections ($CV < 0.3$). Despite of the differences in methodology and input data, the three global water models produce narrower ranges of industrial and domestic water use projections for these countries compared to countries in the developing world and emerging economies. Thus future changes in water use projections of industrialized countries are apparently more robust.

We consider the following reasons for attributing a higher confidence in future water use calculations of developed countries: i) the scenario assumptions (i.e., technological changes according to SSPs narratives) and associated input data sources (e.g., GDP, electricity production, energy consumption) are more consistent with one another; ii) the future change in socio-economic development is relatively stable so that the change is rather insensitive to the different methodological approaches of the models, and 3) the input variable of total electricity production (which does not increase as strong as in the developing world) dominates the calculation of (sub-)sectoral water use intensity for the three models.

In order to investigate reasons for the major differences among the three global water models we now scrutinize regional trends in industrial water withdrawals projections

(Figure 6) to highlight the uncertainty in water use projections we selected major water users with significant different projections across the three models. Each country has been assigned to a hydro-economic classification, for which a consistent set of assumptions for technological and structural change has been developed under each SSP (see Table 2 and 3).

In the mature, industrialized economy of the USA and Germany, the projected industrial water withdrawals exhibit a steadily decreasing trend toward the year 2050 for almost all projections. However, H08 features an increasing trend (after a sharp drop in 2020) for both countries under the SSP3 scenario.

For the emerging economies (China, Brazil, and Russia), the ensemble projections show large differences among the three global water models. WaterGAP projects a much larger net increase in industrial water withdrawals for China and Brazil by 2050 under all SSPs, while H08 shows a net decrease under SSP1 (China, Brazil, Egypt and Russia) and SSP2 (Brazil and Russia). PCR-GLOBWB follows a similar trend with WaterGAP for China and Russia, but shows a much lower net increase for Brazil compared to WaterGAP. For PCR-GLOBWB and WaterGAP, the relative increase is similar for China and Russia. However, the use of different datasets at the reference year (2005) results in a large difference in absolute amounts by 2050. This is particularly obvious for Russia where the industrial water withdrawals differ by a factor four at the reference year between PCR-GLOBWB and WaterGAP. Larger volume of industrial water withdrawals estimated by WaterGAP in emerging economics is often due to manufacturing water use. H08 and PCR-GLOBWB do not disaggregate the industrial sector into manufacturing and electricity, which results in a homogeneous response in projected trends among these sub-sectors. In India, Brazil, and China where the economy is projected to grow rapidly in the coming decades, industrial water withdrawals is projected to increase by more than a factor of two by 2050. In Saudi Arabia, the use of different datasets for the reference year causes a large spread in the ensemble projections.

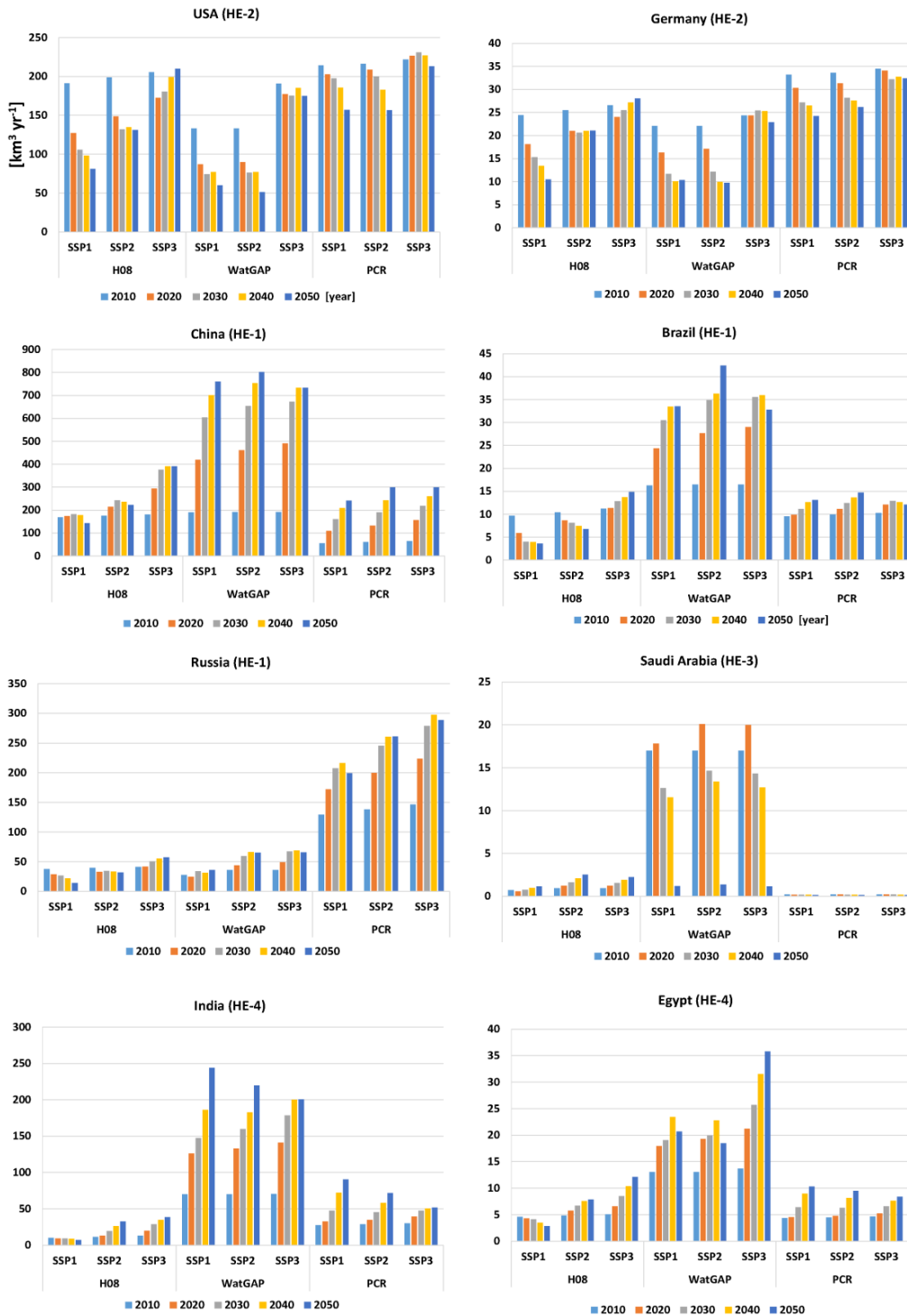


Figure 6. Regional industrial water withdrawal (water demand) projections with three global water models: H08, WaterGAP, and PCR-GLOBWB (PCR) for the year 2010, 2020, 2030, 2040, and 2050 respectively under three SSPs scenarios (SSP1, SSP2, and SSP3). HE denotes the hydro-economic classification (see section 2.2)

6.3 Domestic water use sector

Contrast to the industrial sector, domestic water use is calculated in a similar manner among the three global water models, and is driven primarily by population numbers and per capita water use (or withdrawal). All three models calculate both water withdrawal and consumptive water use, the latter subtracting the return flow to the rivers and groundwater. Domestic water use is distributed to a 0.5 degree by 0.5 degree longitude-latitude grid according to the gridded population numbers for all three models. While H08 and WaterGAP primarily use population numbers and per capita water use as input socio-economic variables, PCR-GLOBWB additionally considers the change in GDP, total electricity production, and energy consumption for the calculation of per capita water use and associated future trend similar to the water use intensity calculation in the industrial sector.

Figure 7 shows ensembles of global domestic water withdrawal projections. Due to rapid increase in world population, ensemble results among the three models show a sharp increase in domestic water withdrawals under all SSP scenarios. Global amount is projected to reach 700-1500 km³ yr⁻¹ by 2050, which is an increase by 50% to 250% compared to the present water use intensity (400-450 km³ yr⁻¹).

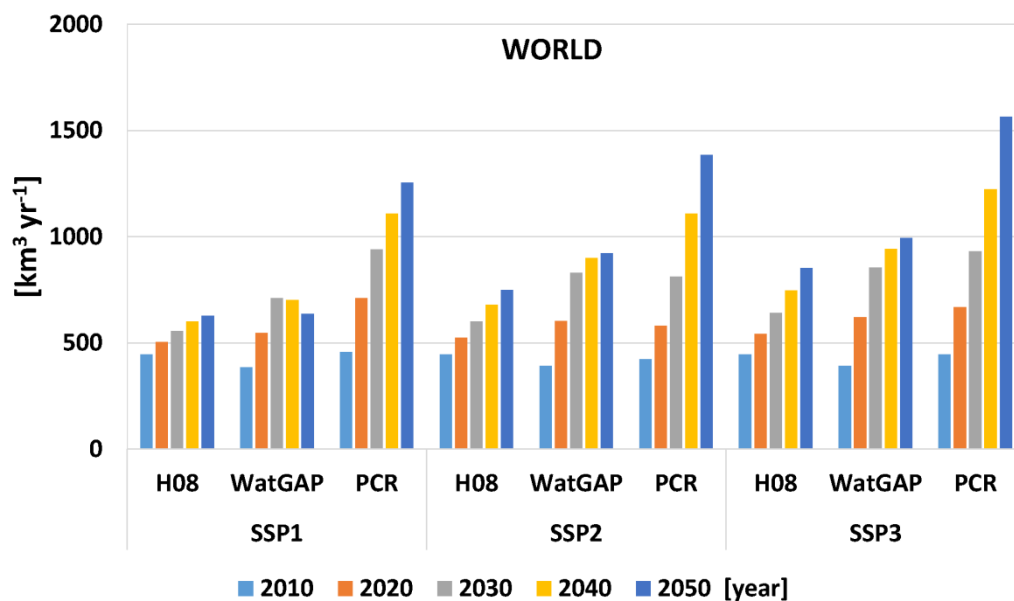


Figure 7. Global domestic water withdrawal (water demand) projections with three global water models: H08, WaterGAP, and PCR-GLOBWB (PCR) for the year 2010, 2020, 2030, 2040, and 2050 respectively under three SSPs scenarios (SSP1, SSP2, and SSP3).

All three models project a consistently increasing trend for future domestic water use by 2050, with a minor exception for WaterGAP, which projects a slight decrease in domestic water use after 2040 under the SSP1 scenario. However, compared to the present water use, WaterGAP still projects a 70% increase by 2050 under SSP1. One obvious difference is that PCR-GLOBWB projects a much higher increase in domestic water use by 2050 compared to H08 and WaterGAP. The increase by 2050 ranges between 40% and 70% (SSP1), 70% and 140% (SSP2), and 90% and 150% (SSP3) for H08 and WaterGAP

respectively, while it reaches 170% (SSP1), 230% (SSP2), and 250% (SSP3) for PCR-GLOBWB.

Figure 8 shows global maps of projected domestic water withdrawals for SSP2 calculated from the ensemble of three water models. Annex III presents the same maps for the SSP1 and SSP3 scenarios. For domestic sector, the model agreement is rather high for almost all countries under the present condition ($CV < 0.3$). However, by 2050, the ensemble projections diverge and the model agreement becomes much lower for some countries such as Russia, China, Australia, and some countries in Central Asia (e.g., Afghanistan) and Africa (e.g., Ethiopia).

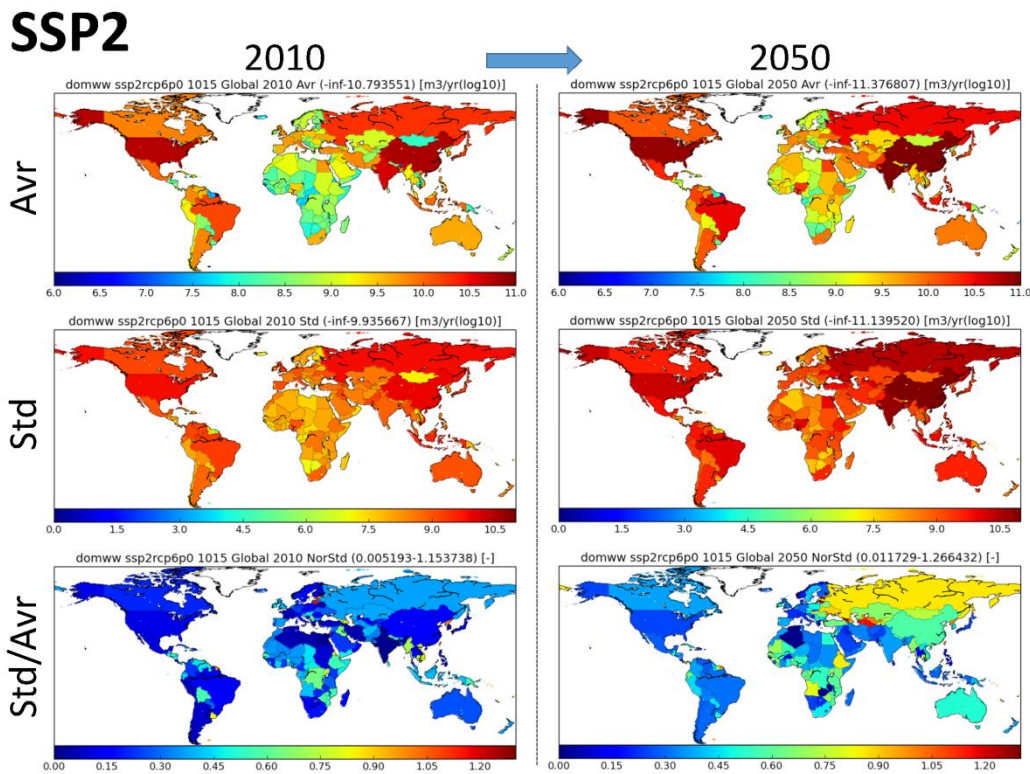


Figure 8. Ensemble statistics of three global water models for domestic water withdrawals (water demand), for 2010 and 2050, SSP2 scenario. *Avr* (Average), *Std* (Standard deviation), and *Std/Avr* denotes the coefficient of variations (CV).

Figure 9 shows again a regional water use for the same set of countries but for the domestic sector. For the USA and Germany, the projected trends in domestic water withdrawals show rather mix signals by 2050 among the three models. H08 shows a steadily increasing trend for the both countries under all SSPs. For WaterGAP, the domestic water withdrawals are projected to increase by 2020 to 2030, but afterwards it decreases towards 2050 under all SSPs. The decrease is much larger under SSP1 in which the domestic water withdrawals are projected to decrease by 10-20% compared to the present water use amount. PCR-GLOBWB projects for the USA a rapid increase in

domestic water withdrawals by 2050 under all SSPs, but for Germany a moderate or negligible increase under SSP1 and SSP2 and a large increase under SSP3.

For China, Brazil, India, and Egypt where present domestic water use shares altogether one-third of the global total and population is projected to grow more rapidly than other countries, ensemble projections show rather a consistent pattern per water model for each country. H08 projects an increasing trend by 2050 under all SSPs and the increase is much larger for SSP2 and SSP3 than SSP1. For PCR-GLOBWB, the projections show a steep increase under all scenarios. There is a pronounced increase in countries with large population growth (China, India, Egypt, Brazil) where the amount of domestic water withdrawals is projected to quadruple in almost all scenarios and water models. For Russia, PCR-GLOBWB projects a pronounced increase similar with China, Brazil, India, and Egypt under all SSPs, while H08 and WaterGAP shows rather a constant or decreasing trend towards 2050 under almost all SSPs except H08 projecting a slight increase under the SSP3 scenario. Similar to the industrial sector, the initial value at the reference year (2005) has a large difference between PCR-GLOBWB and the other two models, which results in a large spread in absolute amounts by 2050. This is also the case for Germany, but between WaterGAP and the other two models. Ensemble projections show a consistent pattern for Saudi Arabia among the three models under all SSPs, and the domestic water withdrawals are projected to increase by 100-200% by 2050.

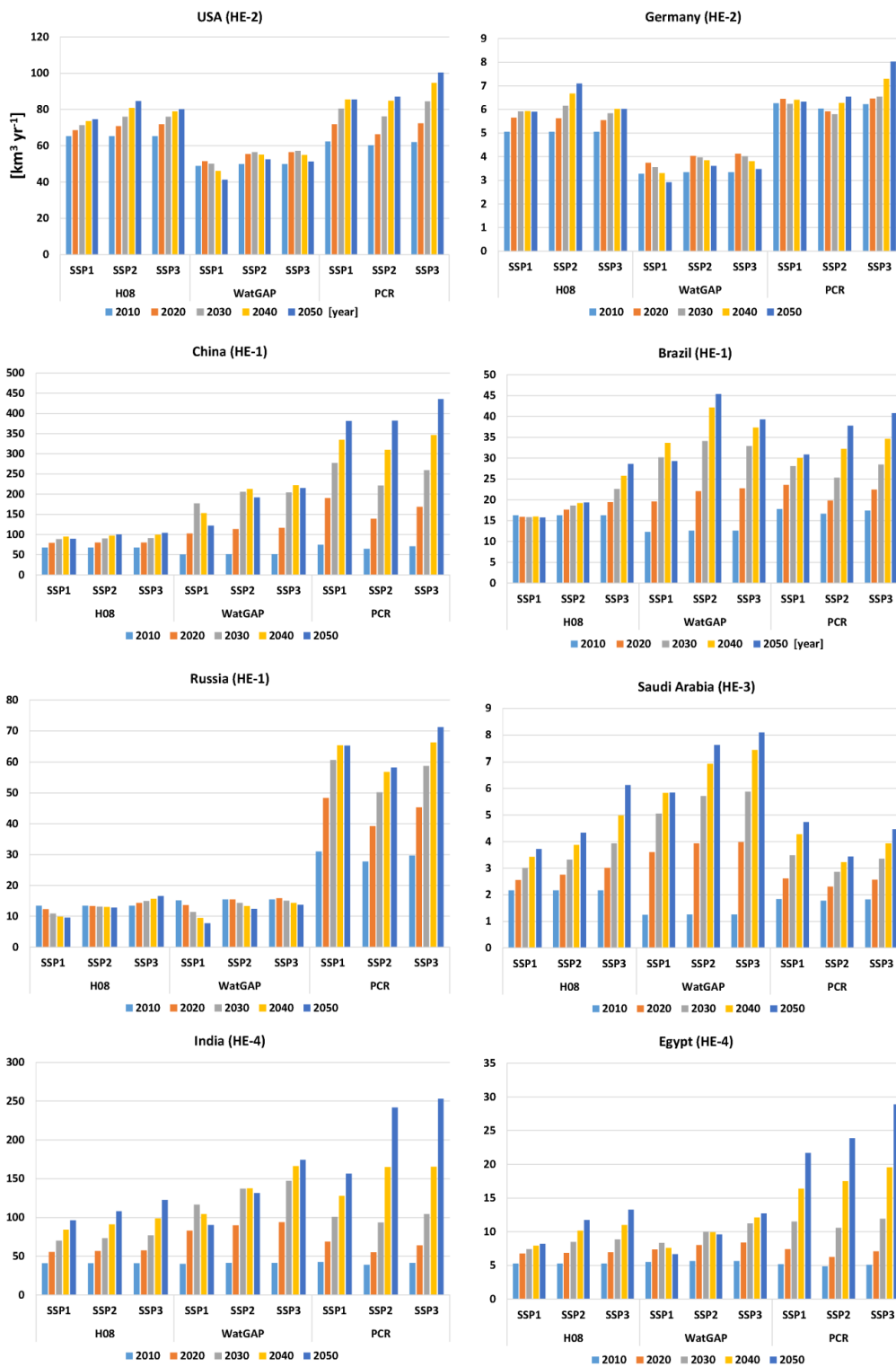


Figure 9. Regional domestic water withdrawal (water demand) projections with three global water models: H08, WaterGAP, and PCR-GLOBWB (PCR) for the year 2010, 2020, 2030, 2040, and 2050 respectively under three SSPs scenarios. HE denotes the hydro-economic classification (see section 2.2)

6.4 Discussion: Sensitivity of modelling approaches on the results

Our first global water use model intercomparison shows a remarkable difference among the three global water models (H08, PCR-GLOBWB, and WaterGAP) used, despite the harmonized socio-economic drivers (population, economy, and energy use) and assumptions on technological and structural change. Thus our current capability in simulating global water use is still uncertain. For the municipal sector, domestic water uses of the ensemble projections are comparable at the global level, although regional trends show significant difference for some countries (*e.g.*, China, India, Russia). Projected industrial water withdrawals are substantially different among the three models. Here we discuss different sources of the uncertainty causing the large spread in the ensemble of water use projections.

A major difference among the employed water models relates to the sector details and the number of input socio-economic variables employed in the calculation procedures.

In general, global water models use more or less different methodological approaches to estimate sectoral water use. This is also true for the three water models applied in this study. As previously noted, H08 and PCR-GLOBWB determine water use for an aggregate industry sector. However, H08 uses primarily total electricity production, while PCR-GLOBWB uses GDP and total energy consumption in addition to total electricity production. For H08 and PCR-GLOBWB, these variables are used to estimate the future change in water use intensity by constructing the future trend, rather than actually calculating the absolute amount of industrial water use.

In contrast, WaterGAP separates water use for the thermal electricity production and the manufacturing industry, and uses those for the calculation of absolute amounts of these sub-sectoral water uses for each year. Therefore more complex functions are used where either electricity or manufacturing water use can dominate the future change in industrial water use. For example, projected industrial water use is dominated by the manufacturing sector in Brazil, Pakistan, Indonesia, and Mexico, and by the electricity sector in China, the USA, and Canada. In the H08 and PCR-GLOBWB models, detailed changes in manufacturing or electricity water use cannot be captured as water use is estimated for an aggregate industry sectors.

Although estimated water use intensity by H08 and PCR-GLOWB has been validated and compared well with reported statistics (*e.g.*, FAO AQUASTAT, EUROSTAT, country statistics) for a historical period (*e.g.*, 1960-2010), this may not be suitable for future assessments which use diverse ranges of scenarios (*e.g.*, SSPs) and associated assumptions on socio-economic and technological change. A simple approach may neglect future dynamic changes in sub-sectoral water use within the industrial sector. For example, SSP scenario narratives correspond to different sources of energy and changes in the economy including structure of GDP. This may result in large variations of sub-sectoral water use intensity across countries.

In addition to the different methodological approaches, we found that the use of different datasets for the reference year (2005) causes a remarkable difference in future amounts of industrial water use. The reference industrial water use at the present condition is globally about 10% lower in H08 than that in PCR-GLOBWB and 20% lower in H08 than that in WaterGAP. The difference among the three models is less obvious for the domestic sector ($\pm 5\%$). Since H08 and PCR-GLOBWB projects the future trend in industrial water use, the use of different datasets for the reference year (*i.e.*, the starting

point) immediately impacts the results and subsequent amounts of future water use. This was clearly demonstrated in some countries such as Russia and India. Although we harmonized the driver data on socio-economics (GDP, population, energy) and assumptions on technological and structural change, the use of the same reference dataset was not considered in the WFaS ‘fast-track’ assessment. This is partly related due to lack of available data for much of the world on water withdrawals and consumptive use, particularly in industry. Locations of water users, water efficiency technological changes over time, and quantities of water withdrawals are largely unknown, and although the general factors that influence water demand are known, we often do not have enough information to show statistical significance.

H08 and PCR-GLOBWB estimate their initial water withdrawal based on the widely used AQUASTAT data from the FAO. AQUASTAT compiles country reported statistics of sectoral water use including a quality check. In WaterGAP the initial water use for the year 2005 is based on own compilation of statistical sources from individual countries. Reasons for apparent differences between these two approaches, both using statistical data reported by countries, were not investigated and are therefore unknown. Improvements in available data could be achieved by bottom-up assessments such as investigation of individual water uses within the sectors and their influence on total demand for that sector.

For example, household water uses for toilets, showers, washing machines, dishwashers can be assessed along with technological changes in the appliances leading to improved water use efficiency over time, methods that have been investigated by WaterGAP. For industry the information sources used for water footprinting can be applied to better estimate water uses for different types of industry. Environmental economic accounting systems and water extended input-output modelling can provide data sources of water use intensities across sectors and can be used to assess changes over time in these industries. However applying this at the global scale may be challenging and involve significant data compilation work. Nevertheless, the use of the same reference dataset for the starting year should be considered in a next water use model intercomparison. Improved information can lead to the use of global water models for policy guidance and assessment of water management.

Using different sets of driver input socio-economic variables also results in significant differences. H08 was the only model that projects globally a decreasing trend in future industrial water use under the SSP1 scenario. PCR-GLOBWB and WaterGAP shows an opposite trend. H08 relies primarily on total electricity production to estimate the future trend. PCR-GLOBWB uses GDP and total energy consumption in addition to total electricity production. WaterGAP uses two more additional input variables, thermal electricity production and manufacturing value added. Future trends in industrial water use projections are similar among the three models for those developed countries that correspond to the HE-2 classification (*e.g.*, USA and Germany). H08 projects a decreasing trend under SSP1 for those emerging economies that correspond to HE-1 and HE-4. Apparently, projected increases in total electricity production are counterbalanced by assumed improvements in water use intensity due to technological changes. In contrast PCR-GLOBWB and WaterGAP projects a consistently increasing trend under the same scenario due to increasing GDP. However, it should be noted that the composition of GDP in the ‘Sustainability’ scenario SSP1 is not known.

There are some differences in projected trends between PCR-GLOBWB and WaterGAP, but this is mainly attributable to the difference in sub-sectoral water uses calculation (aggregated vs. disaggregated). The use of socio-economic variables such as GDP and energy consumption makes the different trend in PCR-GLOBWB and WaterGAP compared to that in H08. This was also the case for the domestic sector in which PCR-GLOBWB projects much higher increase in water use intensity by 2050. H08 and WaterGAP primarily uses population numbers and per capita water use. PCR-GLOBWB additionally use GDP, total electricity production, and energy consumption. GDP projections in the SSP scenarios increase significantly for almost all countries, particularly in emerging economies. The increase in total electricity production is much milder due to improvement in energy use intensity (*i.e.*, higher electricity production per unit energy use), and technological and structural improvement. The calculation of (sub-)sectoral water use intensity using different sets of socio-economic variables should be further investigated.

7. Conclusions

Global water models use simple yet diverse approaches to estimate water use per sector. The results produced from our first global water use model intercomparison showed a remarkable difference among the three global water models (H08, PCR-GLOBWB, and WaterGAP) used in the WFaS ‘fast-track’ analysis. Although we harmonized driver input data socio-economics and assumptions on technological and structural change, ensemble projections for the first half of the 21st century water use showed large variability among the three models and the spread was much larger in the industrial sector compared to the domestic sector.

At the global level the signal of changes in future water use from the water models is as strong as the signal from the three scenarios employed. Although there is a high degree of variability across models and scenarios, all projections indicate significant increases in future industrial and domestic water uses. Despite of potential model and data limitations, the WFaS initiative advances an important step beyond earlier work by attempting to account more realistically for the nature of human water use behavior in the 21st century and to identify associated uncertainties. Our results can be applied to assess future sustainability of water use under envisaged population growth and socio-economic developments.

We also suggest key findings for reducing uncertainty in global water use modeling and improve the robustness in water use projections in the 21st century. We also address future perspectives of global water use model intercomparison and possible improvements for a next step of global water use calculations.

First, the estimates are currently helping to identify hot spots where further investigation is needed, and in some cases may be used to test the implications of broad management and policy options, such as efficiency improvements.

Second, the coarseness of current estimates and assumptions produce questionable results in some areas (*e.g.*, Africa). This makes it very difficult to test and compare benefits of water management options including areas where solutions are most needed.

Third, as greater demands are placed on water resources and they become increasingly scarce, we will need to improve our estimates to better assess the costs and benefits of a variety of water, energy, and land management strategies.

Fourth, regarding input driver data, a disaggregation of the SSP scenario GDP projections into main sectors (agriculture, industry, services) would be of great benefit for improving the linkages between economic growth and water use.

Fifth, current water use modeling approaches can be improved in the following ways: (i) Harmonize the reference dataset for a starting year under the present condition; (ii) Disaggregate industrial sector into thermal electricity and manufacturing sector to incorporate the future dynamics of sub-sectoral water use; (iii) Improve/gather more accurate information on present day water use.

References

- Alexandratos, N. & Bruinsma, J., 2012. *World agriculture towards 2030/2050: The 2012 revision*, Rome: FAO.
- Arnell, N. & Lloyd-Hughes, B., 2014. The global-scale impacts of climate change on water. *Climatic Change*, Volume 122, pp. 127-140.
- Commission, E., 2008. *Directive 2008/1/EC concerning integrated pollution prevention and control*, Brussels: European Commission.
- Cosgrove, W. et al., 2015. *Conceptual framework for scenarios development in the Water Futures and Solutions project*, Laxenburg: International Institute for Applied Systems Analysis (IIASA).
- Döll, P. et al., 2012. Impact of water withdrawals from groundwater and surface water on continental water storage variations. *J. Geodyn.*, Volume 59-60, pp. 143-156.
- Döll, P., Kaspar, F. & Lehner, B., 2003. A global hydrological model for deriving water availability indicators: model tuning and validation. *J. Hydrol.*, Volume 270, pp. 105-134.
- Fischer, G., Hizsnyik, E., Tramberend, S. & Wiberg, D., 2015. *Towards indicators for water security - A global hydro-economic classification of hydrological challenges and socio-economic coping capacity*, Laxenburg, Austria: International Institute for Applied Systems Analysis.
- Flörke, M. et al., 2013. Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. *Global Environmental Change*, Volume 23, pp. 144-156.
- Flörke, M. et al., 2013. Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. *Global Environm. Change*, Volume 23, pp. 144-156.
- Hanasaki, N. et al., 2013. A global water scarcity assessment under shared socio-economic pathways—part 2: water availability and scarcity. *Hydrol Earth Syst Sci*, Volume 17, pp. 2393-2413.
- Hanasaki, N. et al., 2008. An integrated model for the assessment of global water resources – Part 1: Model description and input meteorological forcing. *Hydrol. Earth Syst. Sci.*, Volume 12, pp. 1007-1025.
- Hanasaki, N. et al., 2008. An integrated model for the assessment of global water resources – Part 2: Applications and assessments. *Hydrol. Earth syst. Sci.*, Volume 12, pp. 1027-2008.
- IIASA, 2015. *SSP Database*. [Online]
Available at: <https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&page=about>
- Koch, H. & Vögele, S., 2009. Dynamic modelling of water demand, water availability and adaptation strategies for power plants to global change. *Ecological Economics*, Volume 68, pp. 2013-2039.

- Magnuszewski, P., Grey, D. & Wiberg, D., 2015. *Scenario Focus Group Workshop Report (Paris 4-6 November 2013)*, Laxenburg, Austria: International Institute for Applied Systems Analysis.
- Markewitz, P. & Vögele, S., 2001. *Der Strommarkt in den neuen Bundesländern : derzeitiger Stand und mögliche Entwicklung bis zum Jahr 2050*, Jülich: Forschungszentrum Jülich.
- Messner, S. & Strubegger, M., 1995. *User's guide for MESSAGE III. WP-95-96*, Laxenburg: International Institute for Applied Systems Analysis (IIASA).
- Moss, R. et al., 2010. The next generation of scenarios for climate change research and assessment. *Nature*, 463(7282), pp. 747-756.
- O'Neill, B. et al., 2011. *Meeting Report of the Workshop on the Nature and Use of New Socioeconomic Pathways for Climate Change Research.*, Boulder, Colorado, USA: National Center for Atmospheric Research (NCAR).
- O'Neill, B. et al., 2015. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*.
- O'Neill, B. et al., 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change*, 122(3), pp. 387-400.
- Pastor, A. V. et al., 2014. Accounting for environmental flow requirements in global water assessments. *Hydrol. Earth Syst. Sci.*, Volume 18, pp. 5041-5059.
- Rao, S. & Riahi, K., 2006. The role of non-CO₂ greenhouse gases in climate change mitigation: long-term. *Energy J Sepc Issue*, Issue 3, pp. 177-200.
- van Vuuren, D. et al., 2011. The representative concentration pathways: an overview.. *Climatic Change*, 109(1), pp. 5-31.
- Wada, Y., van Beek, L. & Bierkens, M., 2011. Modelling global water stress of the recent past: on the relative importance of trends in water demand and climate variability. *Hydrol. Earth Syst. Sci.*, Volume 15, pp. 3785-3808.
- Wada, Y. et al., 2011. Global monthly water stress: II. Water demand and severity of water,. *Water Resour. Res.*, 47(W07518).
- Wada, Y., Wisser, D. & Bierkens, M., 2014. Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. *Earth Syst. Dynam.*, Volume 5, pp. 15-40.
- Wada, Y. et al., 2013. Multimodel projections and uncertainties of irrigation water demand under climate change,. *Geophys. Res. Lett.*, pp. 4626-4632.

AENNX I - Key elements of Shared Socio-Economics (SSP) storylines

Below key elements from the SSP narratives (O'Neill, et al., 2015) are summarized by main topic. Green color indicates own interpretation as narratives did not specifically focus on these topics.

	SSP1	SSP2	SSP3	SSP4	SSP5
SSP Title	Sustainability Taking the green road	Middle of the road	Regional rivalry A rocky road	Inequality A road divided	Fossil-fueled development Taking the highway
Synopsis	Gradually move to sustainability	Past trends & paradigms	Resurgent nationalism with uneven cooperation	Increasing inequalities & fragmentation	"Development first" paradigm
POPULATION					
Population growth	Low, peaks around 2050 and declines	Levels off after 2050	Very high in developing countries	Low growth in developed, high in developing world	Low, peaks around 2050 and declines
Urbanization	Rapid	Follows historic trends	Proceeds slowly	Rapid	Rapid
Education	Large emphasis on education; promotion of higher education levels & gender equality	Some progress but too low investments in low income countries	Low investments in education	Esp. in developing education focus is on producing small, highly educated elite	Development policies emphasize education
ECONOMY / TRADE					
Economic growth	Relatively high, also in developing countries	Moderate growth	Slow growth everywhere	Relatively high	Rapid growth; competitive markets
Trade	Markets globally connected, but emphasis on regional production	Markets globally connected but function imperfectly	World had de-globalized, focus on national/regional interests	Limited trade	Accelerated globalization; High levels of international trade
Poverty	Poverty reduction; Rapid growth of the 'middle class'	Poverty remains a challenge for many disadvantaged populations	Pockets of extreme poverty persist	Poverty reduces at the global level, but persists or even worsens in some regions; Slow expansion of global middle class	Strong reduction of extreme poverty; Emergent global middle class stabilizes
INSTITUTIONS / GOVERNANCE					
Institutions	Effective institutions oriented toward cooperation and sustainability principles	Relatively weak coordination & cooperation among national & international institutions	Weak, ineffective institutions; no capacities for global problem solving	Weak / poor access to institutions by low-income regions	Effective institutions foster competitive markets; strong rule of law, low corruption
Global governance	Global focus increases social cohesion	Imperfect global governance	Lack of cooperation, consensus and effective global leadership	Self-interests dominate	Removal of market entry barriers for disadvantaged population groups

	SSP1	SSP2	SSP3	SSP4	SSP5
SSP Title	Sustainability Taking the green road	Middle of the road	Regional rivalry A rocky road	Inequality A road divided	Fossil-fueled development Taking the highway
TECHNOLOGY					
Technological progress	Rapid technological progress	Moderate pace, no major break through	Slow progress (due to low investments)	Rapid, driven by well-educated elite	Rapid, seen as major driver of development
ENVIRONMENT / RESOURCE USE					
Environment	Strict regulations, effectively enforced safeguard the environment	Environmental preservation is restricted to selected high-income regions	Serious environmental degradation in some regions	Strong regional variation in safeguarding environmental resources	Tendency to decouple human-engineered from natural systems
Resource use intensity	Strong decrease	Moderate decrease	Increasing	Overall increasing with regional exceptions	Resource intensive lifestyle
Energy source mix	Renewables increase in importance; Phase out of subsidies on coal and oil	Continued reliance on fossil fuels incl. unconventional oil and gas resources; but overall slowly decreasing fossil fuel dependency	Increasing fossil fuels reliance; push to develop unconventional fossil fuel resources	Underinvestment results in volatile and rising oil and gas prices, which lead to some diversification of the fuel mix	Strong reliance on fossil fuels and exploitation of abundant fossil fuel resources
LIFESTYLES / VALUES					
Sustainability concerns	High emphasis	Relatively low	Limited environmental concerns results in poor progress towards sustainability	Only on local scale	Only on local scale
Consumption patterns	Low material growth and lower resource & energy intensity; Diet with low level of animal products	Consumption oriented towards material growth; growing consumption of animal products	Resource-intensive consumption	Resource-intensive consumption	Resource-intensive consumption globally; Meat rich diets globally
Equality / Social cohesion	Reducing inequality (globally & within economies)	Significant heterogeneities within & across countries	Large disparities within and across countries	Weak political power for less-affluent groups; Low social cohesion; Increasing stratification	Social cohesion is strengthened in most world regions

Annex II. Global maps of industrial water withdrawals

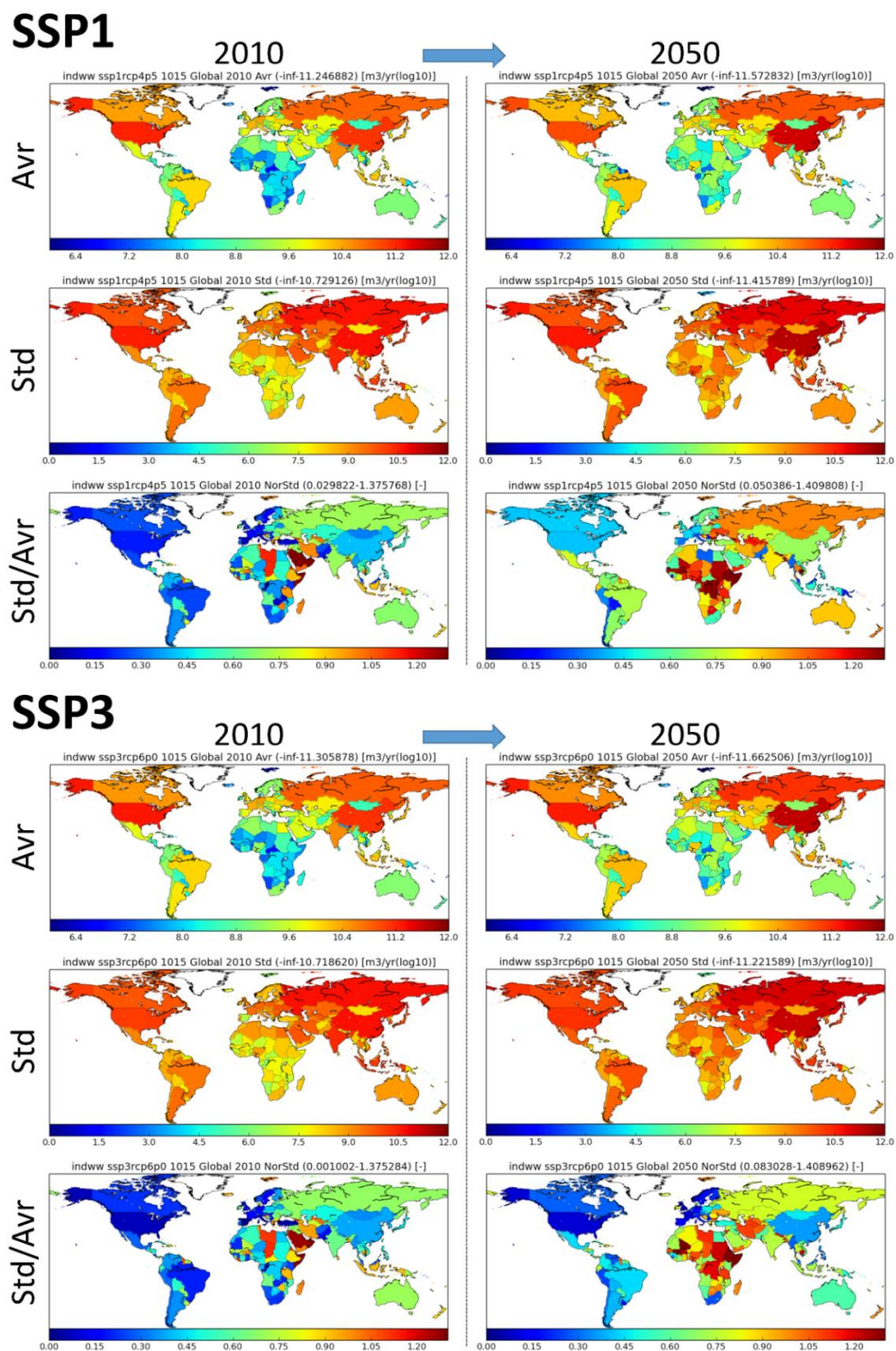


Figure A2. Ensemble statistics of three global water models for industrial water withdrawals (water demand), 2010 and 2050, SSP1 and SSP3 scenario.

Avr (Average), Std (Standard deviation), and Std/Avr denotes the coefficient of variations (CV).

Annex III. Global maps of domestic water withdrawals

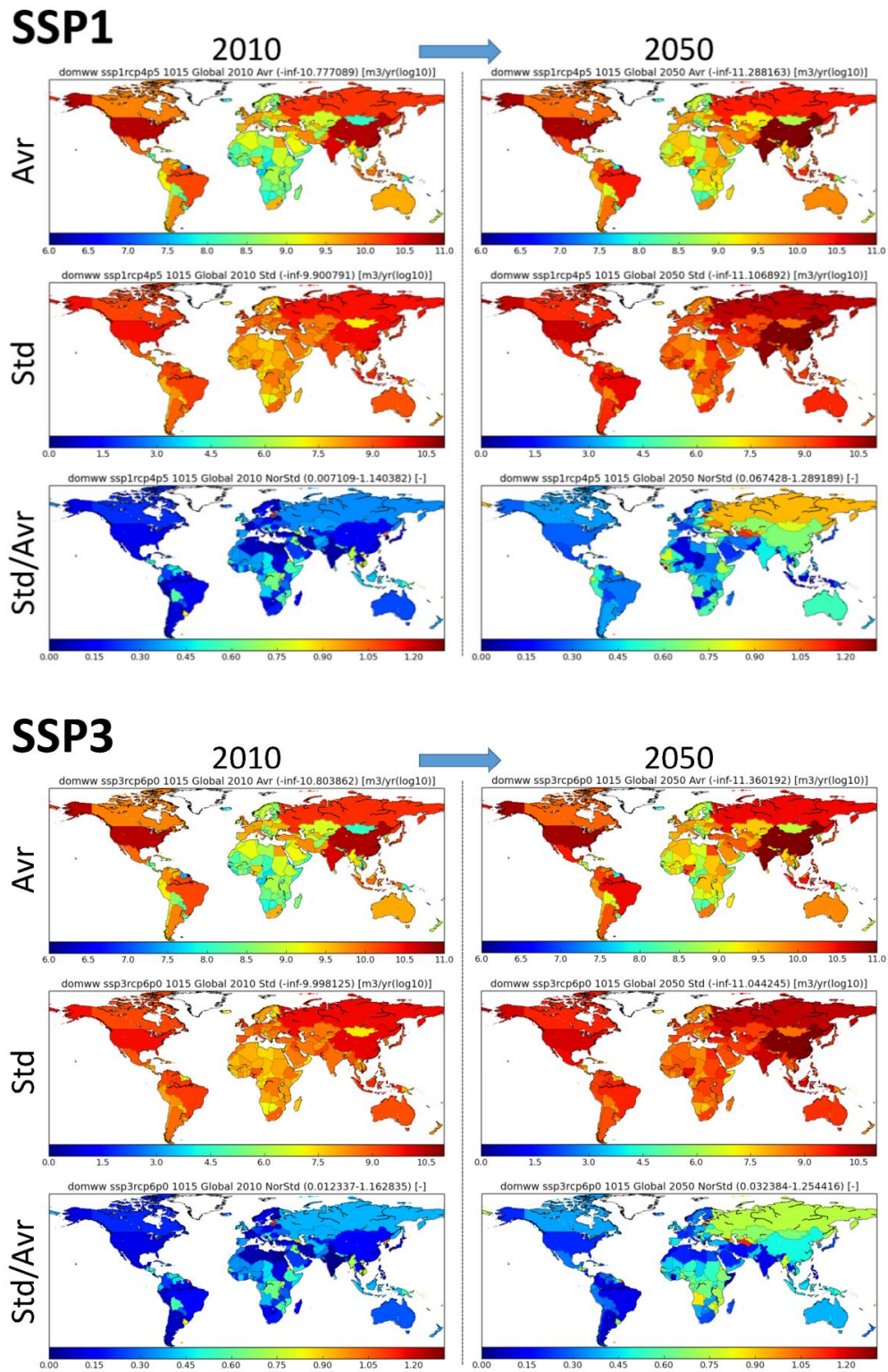


Figure A3. Ensemble statistics of three global water models for domestic water withdrawals (water demand), 2010 and 2050, SSP1 and SSP3 scenario. Avr (Average), Std (Standard deviation), and Std/Avr denotes the coefficient of variations (CV).