Multi-model and multi-scenario assessments of Asian water futures: the Water Futures and Solutions (WFaS) initiative

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Key points:

- A first assessment of Asian water futures using multi-model and multi-scenario approach
- 1.6-2 billion people are projected to experience severe water stress conditions in Asia by 2050
- Socioeconomic changes have critical impacts on water security and are found to be a main driver of growing water scarcity in Asia

Abstract

This paper presents one of the first quantitative scenario assessments for future water supply and demand in Asia to 2050. The assessment, developed by the Water Futures and Solutions (WFaS) initiative, uses the latest set of global climate change and socioeconomic scenarios and state-of-the-art global hydrological models. In Asia, water demand for irrigation, industry and households is projected to increase substantially in the coming decades (30-40% by 2050

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/2016EF000503

compared to 2010). These changes are expected to exacerbate water stress, especially in the current hotspots such as north India and Pakistan, and north China. By 2050, 20% of the land area in the Asia-Pacific region, with a population of 1.6-2 billion, is projected to experience severe water stress. We find that socioeconomic changes are the main drivers of worsening water scarcity in Asia, with climate change impacts further increasing the challenge into the 21st century. Moreover, a detailed basin-level analysis of the hydro-economic conditions of 40 Asian basins shows that although the coping capacity of all basins is expected to improve due to GDP growth, some basins continuously face severe water challenges. These basins will potentially be home to up to 1.6 billion people by mid-21st century.

Keywords. Asia; water scarcity; socioeconomic development; climate change; hydro-economic analysis

Introduction

The pressure on water resources has been mounting and continues to grow worldwide, driven by growing food and energy demands and increasing standards of living, and complicated by regional water governance [*Kahil et al.*, 2015a; *Vörösmarty et al.*, 2000; *Wada et al.*, 2016]. Global water withdrawals have increased sixfold in the last century, which is almost twice the rate of human population growth [*Falkenmark*, 1997; *Shiklomanov*, 2000; *Vörösmarty et al.*, 2005; *Wada et al.*, 2013a]. This huge abstraction of water resources has resulted in many regions undergoing pervasive water scarcity conditions, notably Asia and Pacific regions (hereafter we refer to these two regions collectively as Asia [*Asian Development Bank*, 2016]) [*Schewe et al.*, 2014].

Home to almost 4.5 billion people, Asia has experienced unprecedented economic and population growth in recent decades. Countries such as India and China, during certain periods, have experienced close to double-digit GDP growth, driven by agricultural, manufacturing and export industries. At present, water withdrawals in Asia represent 65% of the global total, and in many parts of Asia, withdrawals are already exceeding available renewable freshwater resources, resulting in many river tributaries losing their capacity to sustain human activities and ecosystem functioning, and causing large economic and environmental costs [*Asian Development Bank*, 2013]. Currently, more than 1.2 billion people in Asia, approximately 30% of the population, are exposed to water stress [*Wada et al.*, 2011a].

The imminent global changes from climate change and socioeconomic development in Asia are expected to place additional pressures on water resources in the coming decades. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change indicates that water scarcity is expected to be a major challenge for most of Asia as a result of growing water demand, supply deficit, and inadequate water management policies [*Hijioka et al.*, Accepted Article

2014]. Climate change will affect both the amount and timing of water supply and the recurrence and intensity of extreme events [*IPCC*, 2012]. For instance, most Asian countries are expected to experience increases in the land area under drought conditions (5-20%) by the end of this century [*Prudhomme et al.*, 2014]. Water demand is projected to increase with population growth and economic development, with some recent studies [*Hanasaki et al.*, 2013a; b; *Wada et al.*, 2016] projecting substantial increases of water demand in Asia in the coming decades. The consequences of global changes could be detrimental to agriculture, health, income and property, with GDP losses reaching 7-10% by 2050 in Central and East Asia [*World Bank*, 2016].

In such a context, it is imperative to evaluate future water scarcity conditions and identify regions at highest risk in Asia. This will help to facilitate management strategies and adaptation policies, and planning for sustainable development in line with the recently agreed Sustainable Development Goals (SDGs). Numerous previous studies have assessed the impacts of global changes on future water scarcity by using various climate and hydrological models, and different sets of socio-economic projections [*Alcamo et al.*, 2007; *Arnell*, 2004; *Arnell et al.*, 2016; *Gosling and Arnell*, 2016; *Hanasaki et al.*, 2008a; b; *Vörösmarty et al.*, 2000]. Nevertheless, despite the significant contribution of earlier global assessments, few studies have analyzed in detail future water scarcity across the Asian continent [*Hayashi et al.*, 2014; *Immerzeel and Bierkens*, 2012; *Malsy et al.*, 2012]. Moreover, no global or Asian study has yet assessed future water scarcity with the latest set of global change scenarios combining the Shared Socio-economic Pathways (SSPs) with the Representative Concentration Pathways (RCPs) in a multi-model framework. Lastly, assessing the water scarcity condition in Asia remains an important scientific challenge. Recent multi-model studies show varying levels of model agreement across the continent, with the highly populated south and east Asian regions often showing highest levels of model uncertainty

[Gosling and Arnell, 2016; Schewe et al., 2014]. Model uncertainty of hydrological models is often high for Asia compared to other global regions (for example due to large uncertainties in precipitation [Arnell et al., 2016]), and these uncertainties carry through from climate models to impact models [Eisner et al., 2017] and water scarcity indices [Samaniego et al., 2017]. Thus, framework approaches that robustly cover uncertainties in climate, hydrological and socioeconomic projection are needed, particularly for Asia.

To address this gap in the literature, this paper presents three alternative projections of Asian water futures to the 2050s, with the objective of demonstrating a framework that covers uncertainties arising from climate and hydrological models, and SSP and RCP scenarios. These projections include available water resources, water demand by sector, and the ensuing annual and seasonal water scarcity. Moreover, main drivers of future water scarcity in Asia have been identified. The contribution of this paper relative to previous literature stems from the use of an ensemble of three state-of-the-art global hydrological models (GHMs) at 0.5°×0.5° resolution forced by five downscaled and bias-corrected Global Climate Models (GCMs), and the development and use of an original set of global water scenarios. These scenarios combine water-extended SSP storylines and climate change scenarios based on the RCPs, using the Water Futures and Solutions (WFaS) initiative methodological framework. The WFaS initiative is a collaborative, stakeholder-informed, global effort applying systems analysis to understand water resource challenges and identify a portfolio of policy interventions that work coherently across scales and sectors. The development of this framework has involved an extensive consultation with water experts and stakeholders from around the world in the context of the WFaS Scenario Focus Group [Wada et al., 2016].

The remainder of the paper is organized as follows. Section 2 describes the methodology and the data used in this assessment. Section 3 presents the results of the supply, demand and annual and seasonal stress assessment, followed by Section 4 which presents in further detail a novel assessment on the dynamics of water stress. This includes: attribution of increasing stress to different drivers; an assessment of Asian basins' hydro-climatic complexity and institutional coping capacity using a hydro-economic classification system; and uncertainty and limitation of this experiment. Finally, Section 5 concludes with the summary and policy implications.

1. Methodology

2.1 WFaS scenario approach

A set of global water scenarios based on combinations of the SSPs and RCPs was developed by the WFaS initiative [*Wada et al.*, 2016]. Different SSP and RCP combinations create a framework for climate-related scenario outcomes, describing four climate change pathways (RCP2.6, 4.5, 6.0, and 8.5) and five different global socioeconomic developments (SSP1-5). Many previous studies projected future water supply based only on the RCPs [*Schewe et al.*, 2014]. In contrast, few studies have projected future water demands considering the SSPs [*Arnell and Lloyd-Hughes*, 2014; *Bijl et al.*, 2016; *Hanasaki et al.*, 2013a; b]. This is because the SSPs inherently focus on key climate policy drivers such as GDP, population, and urbanization, but with less attention given to specific sectors including water [*O'Neill et al.*, 2013]. Thus, in collaboration with a group of water planners and stakeholders from around the world, the WFaS initiative and its scientific consortium has extended the original SSP storylines at country level with relevant critical dimensions affecting water availability and use. These dimensions have been assessed qualitatively and quantitatively for each SSP and group of countries based on a two-dimensional hydro-economic (HE) classification system (see section A1 in Appendix for more details), providing a first set of global water scenarios [*Wada et al.*, 2016]. The set of water scenarios are applied to three GHMs to project future water demand of sectors such as energy manufacturing, and households [*Fricko et al.*, 2016; *Wada et al.*, 2016]. An overview of the methodological framework of the WFaS initiative is given in Figure 1.

(Insert Figure 1)

In the scenario development process, countries and basins are characterized based on HE classification. This classification system builds on previous studies to consider water security in a risk-based framework encompassing both the biophysical and institutional features of regions [*Grey et al.*, 2013; *Hall et al.*, 2014; *Sadoff et al.*, 2015]. The HE classes are derived from two dimensions based on (i) exposure to complex hydro-climatic conditions (x-axis), and (ii) economic and institutional capacity to cope with water-related risks (y-axis). Hydro-climatic complexity is determined using a combination of four sub-indicators; per capita available renewable water resources, water use intensity, the monthly variability of runoff, and dependency ratio on external water resources (exogenous runoff). GDP per capita, a measure of economic strength and financial resources, has been selected to proxy the economic and institutional capacity to cope with water-related risks. Additional indicators have been discussed and explored for potential inclusion in a compound indicator to proxy economic-institutional capacity such as the education level, the Human Development Index, and the Worldwide Governance Indicators, among others. However, globally for all countries these indicators are positively correlated with GDP per capita. The potential extension of the y-axis is an ongoing process subject to diverse opinions highlighting the challenge to measure the effectiveness of institutions, management and governance, in particular for future periods. For recognizing the spatial heterogeneity of water challenges, the HE classes are divided into four (HE1 to HE4) representing combinations of hydrological complexity and economic-institutional capacity (Figure 1). Countries in different HE classes are assumed to experience different pathways, such as rates of technological and structural changes in the main water use sectors, and therefore the water scenarios go beyond globally uniform assumptions.

Table B1 in Appendix B summarizes the water-extended SSP scenario assumptions, further detailed in *Wada et al.* [2016]. For irrigation water demand estimation, we have used historical (the year 2000) values for irrigated areas and irrigation efficiency because their future possible values are still being developed in the WFaS framework. Following *Wada et al.* [2016], three future water scenarios based on feasible combinations of SSPs and RCPs have been applied: the Sustainability scenario (SSP1-RCP4.5), the Middle of the Road scenario (SSP2-RCP6.0) and the Regional Rivalry scenario (SSP3-RCP6.0), representing a lower, a middle, and an upper range of plausible changes in future socioeconomics and climate.

2.2 Data and models

Socioeconomic variables for each SSP are available from the IIASA SSP database portal (https://tntcat.iiasa.ac.at/SspDb). The gridded representation of the country-level SSP population dataset used in this study is based on *Jones and O'Neill* [2016]. GDP is downscaled based on the gridded population distribution at a 0.5°×0.5° spatial resolution (roughly 50 km by 50 km at the equator).

WFaS uses a multi-model ensemble of three state-of-the-art GHMs: H08 [*Hanasaki et al.*, 2008a; b], PCR-GLOBWB [*Van Beek et al.*, 2011; *Wada et al.*, 2014a] and WaterGAP2.2 [*Flörke et al.*, 2013; *Schmied et al.*, 2014], to estimate water demand and supply at a 0.5°×0.5° spatial resolution. The GHMs explicitly include anthropogenic activities such as water withdrawals and reservoir operation with fixed reservoir capacity at the year 2000 level based on GRanD reservoir data [*Lehner et al.*, 2011]. *Wanders and Wada* [2015] and *Masaki et al.* [2017] indicate that reservoirs play an important role in mitigating low flow conditions using the same GHMs used in this study. Also, PCR-GLOBWB explicitly calculates groundwater use, while in the other two GHMs groundwater use is implicitly included. Earlier studies with those GHMs suggest that large quantity of groundwater is used to meet water demand in Asia [*Döll et al.*, 2014; *Hanasaki et al.*, 2008b; *Wada and Bierkens*, 2014]. Here water demand covers three main sectors: irrigation, industry (energy and manufacturing) and households, and water supply is defined as river discharge. This study assesses water supply with ten year climatology based on monthly values. For example, we assume that the representative value of the 2010s spans data from the period 2006-2015. On the other hand, water demand is projected every ten years because SSPs provide decadal projections.

The GHMs are forced by five bias-corrected GCMs projections given by the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) fast track [*Hempel et al.*, 2013; *Warszawski et al.*, 2014]. This multi-model approach has been chosen to robustly account for the uncertainties in future projections [*Haddeland et al.*, 2011; *Schewe et al.*, 2014]. Further details of the modeling approach and input data are given in *Wada et al.* [2016].

2.3 Asian future water assessments

We focus on the near-future period in order to make our assessment policy relevant for future water challenges in Asia. This paper assesses water futures in Asia to 2050 on a decadal basis to identify the key drivers of worsening water stress conditions. Changes in Asian water futures are quantitatively investigated with two commonly used indicators [*Alcamo et al.*, 2007; *Kiguchi et al.*, 2015; *Rijsberman*, 2006; *Veldkamp et al.*, 2015; *Vörösmarty et al.*, 2000; *Wada et al.*, 2011a]. Firstly, we present the Water Crowding Index (WCI; hereafter defined as water shortage, and used in Section 3.1) that quantifies the available surface water resource per capita (ASWRpc) categorized as: scarcity (500-1000 $m^3.cap^{-1}.yr^{-1}$), and absolute scarcity (<500 $m^3.cap^{-1}.yr^{-1}$) [*Falkenmark et al.*, 1989]. This indicator is a good proxy for population growth impacts on water supply, and to distinguish between climate and human-induced water scarcity. Secondly, we use the Withdrawal To Availability Ratio (WTA; hereafter defined as water stress, and used in Section 3.3) which is the ratio of total withdrawals for human use to total available surface water resources. Regions are considered water-scarce if the ratio is between 0.2 and 0.4, and severely water-scarce if the ratio is greater than 0.4 [*Raskin et al.*, 1997]. Importantly, we have calculated WCI for both the annual mean and the driest month, and WTA for both the annual and seasonal mean. Section 4.3 presents the HE analysis that includes WCI, along with WTA as its sub-indicator. Note that all results presented in this paper represent the ensemble mean of all combinations of three GHMs and five GCMs for each water scenario, and ranges in future projections stem from the difference among the three water scenarios.

2. Results

3.1 Water supply

Here, water supply is defined as *available surface water resources (ASWR)* and *available surface water resources per capita (ASWRpc)*. ASWR are composed of local runoff and upstream inflow through river networks, i.e., river discharge. Compared to the 2010s, by the 2050s, annual ASWR in Asia will decrease in area by 35% under the Sustainability scenario and 57% under both the Middle of the Road and Regional Rivalry scenarios (Figure 2a). In the Sustainability scenario, annual ASWR decreases significantly in Central and West Asia, south Pakistan, north India, parts of China and Australia. For the Middle of the Road and the Regional Rivalry scenarios even larger reductions are projected over many parts of Asia including Afghanistan, Nepal, Myanmar, Papua New Guinea and Japan, in addition to the regions indicated above. Approximately 30% of the area in Asia shows a consistent reduction in ASWR under all scenarios in the 2050s (See Figures B1 and B2 in Appendix for more details). It should be noted that the reduction in the driest month is often the most critical because of high seasonality in Asia (Figure 2b). Depending on scenarios, it is expected that by the 2050s between 41-58% of land area in Asia will get drier in the driest month. India to Myanmar and south to east China will suffer substantial reductions in ASWR during the driest month.

(Insert Figure 2)

When the local population is considered, ASWRpc can be low even if a region has high ASWR, such as south India and south and east China (Figure 2c). When it comes to change in the future, a trend can be opposite between ASWR and ASWRpc. Although ASWR will increase in many parts of South Asia by the 2050s in the Sustainability scenario, ASWRpc is expected to decrease as a result of rapid population growth. In northeastern China, Pakistan and India, low ASWRpc is driven primarily by high population densities, whilst in Turkmenistan, Uzbekistan and northwestern China it is driven by low ASWR (Figure 2d). In other areas, reductions in ASWRpc are due to both climate change and the effects of population growth. Rapid urbanization is expected to result in more localized impacts not necessarily reflected at the country and grid-scale. Table B2 in Appendix B gives an overview of ASWRpc at country level, where China, Georgia, Japan and the Republic of Korea are the only countries with no reduction in ASWRpc by the 2050s.

Water demand

Figure 3 and Table 1 present projections of total water demand in Asia during the 2010s and the 2050s. The results reveal a trend of increasing water demand in Asia under all SSP scenarios. Depending on the scenario, the total water demand is projected to reach 3200-3500 cubic kilometers per year (km^3/yr) by the 2050s, an increase of 30-40% compared to the present demand of 2400-2420 km^3/yr. This increase is primarily driven by growing industrial and municipal water withdrawals. The Regional Rivalry scenario has the largest increase in demand because it has the highest population growth and the slowest rate of technological change. This is followed by the Middle of the Road scenario and the Sustainability scenario, respectively. By the 2050s, Asia's water demand is projected to be larger than that of all other continents put together, as a result of rapid and intense socioeconomic development. Moreover, a net increase in total water demand is largest by the 2030s, mainly due to the peaking of population growth. The largest increase in water demand between the 2010s and the 2050s is expected to take place in East Asia (+420-550 km^3/yr) and South Asia (+220-310 km^3/yr), which account for almost 80% of total water demand in Asia (Table 1). Water demands in Southeast Asia, and Central and West Asia are expected to grow to 310-360 km^3/yr, and 230-240 km^3/yr, respectively. Conversely, water demand in currently developed countries is projected to remain constant.

(Insert Figure 3.)

(Insert Table 1)

Tables B3-B5 in Appendix B provide details on the sectoral water demands in Asia. Irrigation water demand represents 80% of total water demand and is the largest water user in almost all Asian countries. Irrigation water demand increases induced by climate change are concentrated in China, India and Pakistan, where the majority of irrigated areas occur in Asia [*Wada et al.*, 2013b]. Municipal water demands are projected to rise by more than threefold by the 2050s, escalating from 180-190 km^3/yr in the 2010s to 495-640 km^3/yr in the 2050s. The main drivers are growing incomes, which increase per capita water use, together with rapid population growth and increased urbanization primarily in India, China, Pakistan and Indonesia. Industrial water demand in Asia is projected to reach 650-780 km^3/yr by the 2050s, more than double the present demand of the 2010s (275-290 km^3/yr). The strongest driver is the growth in electricity production and overall energy use in emerging economies including India and China. For currently developed countries, net increase in municipal and industrial water demands is minor because of technological improvements in water use efficiency and the increase in national income, which leads to structural shifts in the industrial sector [*Wada et al.*, 2016].

3.3 Water stress

According to our WTA estimates, large parts of Asia currently experience severe water stress (Figure 4a). The spatial distribution of these severe water stress conditions is in line with findings of earlier studies [*Arnell*, 2004; *Hanasaki et al.*, 2008b; *Oki et al.*, 2001; *Sadoff et al.*, 2015; *Wada et al.*, 2011a; *Wada et al.*, 2011b]. The results indicate that future socioeconomic development and climate change will further exacerbate current water stress conditions in Asia (Figure 4b). Water stress is expected to increase in 74-86% of the total area of Asia depending on scenarios, and approximately 20% of the area in Asia will be under severe water stress by the 2050s in all scenarios. In the coming four decades, most Asian sub-regions show consistently higher WTA than that of the 2010s across the three scenarios (Figure 4c). Exceptions are western India and Japan, which will experience reductions in water stress, because of a wetter climate and reductions in water demand. Despite this, western India will remain a hotspot of water stress. Under the Sustainability scenario, our results project many areas with decreasing water stress including Myanmar, Malaysia, and east Australia.

(Insert Figure 4)

Results of this study indicate that currently around 1.1 billion people in Asia live in areas under severe water stress conditions, equivalent to 30% of the total population in Asia. By 2050, the potential population exposed to these severe conditions is projected to increase by 42-75% depending on the scenario, reaching between 1.6 billion in the Sustainability scenario and 2 billion in the Regional Rivalry (Table 2). In all three scenarios, by 2050, some 40% of Asia's population will be affected by severe water stress conditions. The population exposed to severe water stress in South Asia is expected to reach almost 1 billion by 2050, two-thirds of which will be living in India, Pakistan and Bangladesh.

(Insert Table 2)

Most of Asia experiences strong seasonality in water supply and demand, which can cause severe water stress during the course of the year (Figure 5a). The results for the seasonal water stress for three-month climatology in the 2010s show regions with seasonal severe water stress mainly during their dry seasons, such as areas around Afghanistan, India and southern China, while there are regions which undergo severe water stress conditions throughout the year. One of the key drivers of severe water stress in Asia is high irrigation water demand in the dry season. However, water stress can also occur during wet seasons when water demand is high. These cases spatially correlate reasonably well with areas in which double-cropping irrigation is practiced. By the 2050s, it is expected that seasonal water stress will intensify and areas with severe water stress will expand (Figure 5b). Under the Middle of the Road scenario, the consequence is that one fifth or more (20-23%) of the area will be under severe water stress in the 2050s in every season. The seasonal increase in water stress through the decades is largely consistent in large parts of Asia under all scenarios (Figure B3). Section A2 in the Appendix present more details on seasonal water stress.

(Insert Figure 5)

3. Discussion

4.1 Attributing the increases in water stress

Figure 6 presents the attribution rates of supply and demand in the 2050s for each scenario, showing which component (i.e., water supply and/or water demand) contributes most to the increase in water stress (See Section A3 in the Appendix for methodological details). In areas of no water stress increase, or area of water stress increase with increasing supply or decreasing demand, the cells are marked in white in the relevant supply or demand map.

(Insert Figure 6)

Throughout the three scenarios, increases in water stress over vast areas in Asia are predominantly attributable to increases in water demand. Importantly, significant increases in water stress in the hotspots shown in Figure 4b, such as east and west China and Central and West Asia, are mainly driven by water demand increases. In contrast, a few regions have an attribution rate dominated by changes on the supply side, but these areas rarely fall into hotspots of changes in water stress, except Pakistan and India in the Middle of the Road and the Regional Rivalry scenario. These two exceptions already tend to face severe water stress conditions, and it is projected that these conditions will intensify as a result of reductions in water supply caused by climate change in large areas of the countries. However, the impacts of demand increase are even more obvious in areas that have megacities. By the 2050s, the increasing water stress in Mongolia to north China, coastal and south China, some countries in Southeast Asia, Central and West Asia, and megacities and their surroundings is dominated by changes in industrial and municipal water demand, indicating that socioeconomic changes are more significant than climate change.

These results highlight that increases in water demand have a critical impact on water security and can be a main driver of aggravation of water stress. If socioeconomic changes are the significant drivers of growing water stress, managing these drivers needs effective policy interventions, including better water governance and investment decisions. Conversely, in regions where climate drivers are dominant, adaptation and water management policy must take the impact of climate change, and associated uncertainties, into account.

4.2 Basin-level hydro-economic analysis

In order to discuss the challenges facing adaptation to future water scarcity in Asia, the HE classification (see section A1 in Appendix for more details) was calculated by aggregating grid-level variables for 40 Asian basins (following FAO delineation). The basin-scale analysis highlights the spatial heterogeneities across countries, particularly relevant for large countries such as China and India, and facilitates identifying trans-boundary challenges. Note that this analysis excludes the fourth sub-indicator, the dependency ratio on external water resources, since inflow to a spatial unit from upstream units is zero in the case of the basin-scale analysis. Figure 7a maps Asian basins according to the HE groups in the 2050s under the Middle of the Road scenario. Basins classified in the most vulnerable HE-4 group (high water challenges and low economic-institutional capacity) are concentrated in South Asia and Central and West Asia. Figure 7c presents the trajectory of the HE indicator over time for 20 major basins out of the 40 we examined, selected based on population and spatial extent in the 2010s (Figure 7b). The points in each trajectory denote the decades: 2000s, 2010s, 2030s, and 2050s (Figure B4 shows plots for all 40 basins). The basins are plotted in the HE dimension based on their hydro-climatic complexity (x-axis) and economic-institutional capacity (y-axis). Significant levels of economic growth are projected for all basins, leading them consistently upward in the two-dimensional space. This effect is most pronounced in basins in China (blue lines). Depending on water-related management and achieved spillover of increasing economic strength, the coping capacity for adaptation and risk management related to water challenges should increase. Figure 7c presents (on the x-axis): the developments of the overall HE classification indicator (c1); the individual sub-component indicators: per capita surface water resources (c2); water use intensity (c3); and monthly variability of runoff (c4).

(Insert Figure 7)

In the year 2010, 12 of the selected 20 basins—home to 2 billion people—are categorized as in HE-4 (high water challenge due to the high hydro-climatic complexity and low adaptation capability), while only North Korea, South Korea, and Taiwan are in HE-3 (high water challenge but high coping capacity). By 2050, as a result of economic growth, eight basins have shifted from HE-4 to HE-3, totaling 1 billion people (approx. 20% of the Asian population in the 2050s). However, four basins (Amu Darya, Sabarmati, Indus, and Ganges-Brahmaputra) will remain in HE-4 until the 2050s, despite some improvements in their economic-institutional capacity. These basins remain highly vulnerable in the coming decades and will need particular attention. We also emphasize that three of these four basins (Sabarmati, Indus, Ganges-Brahmaputra), all of which are in South Asia, are all densely populated with an expected 1.5 billion people in the 2050s (approximately 30% of the Asian population). Moreover, all four basins are transboundary, imposing additional management challenges.

Between 2000 and 2050, all basins in Asia (except Japan) will be exposed to increasing levels of hydro-climatic complexity, i.e., they will move to the right in the HE two-dimensional space. The level of hydro-climatic complexity varies widely across basins in East Asia. In contrast, high complexity occurs in all South Asian basins and several East Asian basins, followed by basins in Central and West Asia. Among the 20 selected basins, the Sabarmati, Krishna, and Ziya He Interior show the highest levels of hydro-climatic complexity. The most significant rates of increase in hydro-climatic complexity occur in the Chinese coast and Bo Hai, followed by Amu Darya and Godavari.

The contribution of the individual sub-components to changes in the hydro-climatic complexity indicator between 2010 and 2050 varies. Firstly, regarding per capita surface water resources (Figure 7c2), changes in the indicator are caused by both changing hydrological conditions and population growth. The largest increase (threshold 0.5) among the 20 selected basins occurs in the Philippines, Godavari, Ganges-Brahmaputra, Amu Darya and Indus basins. Conversely, shifts in basins in East Asia, Japan and Korea are not significant, and sub-indicators even decrease, particularly after 2040, due to population decrease as well as hydrological changes.

Secondly, for water use intensity (Figure 7c3), it is obvious that this indicator increases largely across all basins because of the rapid growth of water demand. Our projections indicate steady increases in water demands, even in basins with already-high hydro-climatic complexity, as a result of the tight coupling of industrial and municipal water demand with GDP per capita growth. Consequently, water use intensity is the main driver for changes in the integrated HE-classification index over time. In particular, there are eight basins that show high water use intensity. Their scores of the sub-indicator are greater than 0.8, indicating that water demand in those basins amounts to 60% or more of total renewable water resources according to the definition in the HE analysis (see more detail in Table B2). In practice, when annual or seasonal water demand is close or exceeds available renewable water resources, additional water resources are needed to satisfy the demand. These may include water from non-conventional sources such as desalinated water and wastewater, but also the use of non-renewable groundwater resources which already occurs in many parts of the world with many major aquifer systems undergoing progressive depletion [*Famiglietti et al.*, 2011; *McGuire*, 2011; *Scanlon et al.*, 2012; *Wada and Bierkens*, 2014; *Wada et al.*, 2014a]. Furthermore, the situation might be even more complicated because some basins (e.g. the Indus) are highly dependent on limited glacier meltwater which will be impacted by climate change [*Immerzeel et al.*, 2010]. Note that water demand exceeds available water resources in the Sabarmati and Indus throughout the period. The same is predicted for China Coast, Bo Hai, Huang He, Krishna and Amu Darya by the 2050s.

The third sub-indicator, monthly variability of monthly runoff, indicates strong seasonality particularly for three Indian basins: Sabarmati, Godavari and Krishna, suggesting substantial needs for well-designed water resource management (Figure 7c). Moreover, seasonal variation in these basins will further intensify through to the 2050s. However, in general, shifts in the x-axis for this index are smaller compared to the other two sub-indexes.

As a result of the three indices above, the basins shift in the HE dimension of the integrated HE index (Figure 7c1). Basins with larger rightward shifts in particular need more strategic and effective management to cope with intensifying hydro-climatic complexity in the coming decades. Water use intensity is the most important driver for increasing hydro-climatic complexity. This highlights the particular importance of appropriate water demand management over time, suggesting the need for additional improvements in water use efficiency as a key ongoing priority to reduce water demand. Measures that could potentially improve water use efficiency include technical improvements of water saving equipment used in households, industrial plants and irrigated plots as well as behavioral changes of the society to reduce water use. Examples cover recirculation of water, change in cooling systems of power plants, switching from less-efficient flood irrigation to more-efficient sprinkler and drip irrigation systems, improving crop water productivity with the help of new cultivars or higher efficiency of nutrient application, reducing leakage in water infrastructure, improving water allocation among uses, changing diet from animal-based to plant-based foodstuffs, and reducing food losses and waste [*Jalava et al.*, 2016; *Kahil et al.*, 2015b; *Wada et al.*, 2014b].

Uncertainty, limitation and future improvements

Many studies in the literature have already discussed uncertainty in projections of water supply and demand, and have indicated that both GHMs and GCMs are the main sources of uncertainty, as well as scenarios used [*Haddeland et al.*, 2011; *Schewe et al.*, 2014;

Wada et al., 2013b]. Water scarcity projections presented in this paper show that the choice of GHMs tends to be the dominant source of uncertainty over a large part of Asia, especially in central and southeast Asia. However, uncertainty in southern and eastern China and South Asia, where water stress is severe and will be even worse in the future, mainly results from the choice of GCMs. Overall, scenario differences are less important uncertainty source compared to the choice of GHMs and GCMs.

Our results show a difference among GHMs in the various projections of water demand and supply, despite efforts to harmonize climate forcing data, the socioeconomic drivers and the assumptions regarding technological and structural changes. *Wada et al.* [2016] describes in detail the uncertainty arising from GHMs in our projections of water demands, mainly driven by the different methodological approaches between the GHMs, and the different specification of sectoral boundaries and the drivers of the sectoral water demands.

Three additional factors would potentially make important contributions to this study, but it is not possible to include them, as yet. First, future land use changes including irrigated areas and agricultural technology expansion according to the SSP scenarios are still under development. Instead, we have kept extents of irrigated areas and irrigation efficiency constant at the level of the base year 2000. As a result, in this study climate change is the only driver for future irrigation water use. Future food demand increases will cause some expansion in irrigated areas resulting in additional irrigation water use. At the same time, irrigation efficiency will likely increase, especially in water stressed regions, resulting in decreased levels of irrigation water demand. The combined effect of these two additional drivers pointing in opposite directions on water scarcity will be further investigated when global datasets on future extent of irrigated areas and development of irrigation efficiencies will become available. Second, our projections are largely driven by socioeconomic factors given by the SSP scenarios, such as GDP and population. The projections of these factors do not respond to changes in water availability and the occurrence of extreme climatic events (there is no feedback between climate and socioeconomic development). Third, this study does not take into account environmental flow constraints when estimating future water stress because of the lack of reliable information on the impacts of global changes on ecosystem requirements and the uncertainty underlying existing calculation of environment flow at large scale. However, our results highlight implicitly the potential pressures on ecosystems, driven by the impacts of changing human water use on available water resources. All these aspects should be improved in future assessments to reduce the uncertainty surrounding water stress projections.

Lastly, the study has considered a wide, albeit central range of scenarios, and does not necessarily cover the full possibilities. For example, on the socioeconomic side, Asian GDP projections for SSP4 and SSP5 currently fall outside the range considered. Given the importance of socioeconomic changes in the results, this would likely have effects that are worth further investigation. Whilst for climate change impacts, again consideration of RCP2.6 and RCP8.5 would also magnify the importance of climate impacts – not currently large due to the small difference between RCP4.5 and RCP6.0 between present and 2050.

4. Conclusions

This study has assessed three possible water futures in Asia based on a set of consistent and comprehensive climate and socioeconomic projections using three GHMs. For each scenario, surface water supply; irrigation, industrial and municipal water demand; and consequent water stress have been assessed.

Our results show that socioeconomic changes have the most significant impacts on water demand growth and overall water stress in hotspots in Asia. While population will peak in some countries before the 2050s, population and GDP are expected to increase in almost all countries across Asia. Subsequently, industrial and municipal water demands will increase depending on scenario from current levels by 136-167% and 176-245%, respectively, by the 2050s. *Wada et al.* [2013b] highlighted the impact of climate change on future water demand for irrigation. As a result of rapid water demand growth, water stress is expected to increase considerably in Asia by the 2050s, with 20% of the land area of Asia subject to severe water stress. Climate change is projected to put additional pressures on water resources. By the 2050s, one-third less surface water resources would be available in the medium (RCP6.0) compared to the low emissions scenarios (RCP4.5), a gap that grows towards the end of the century. We emphasize that a particularly extreme intensification of water stress will occur in the current hotspots of water stress, with an estimated 1.6-2 billion people living in regions of severe water stress in the 2050s, an increase of 38-68% from the 2010s. Results of the seasonal analysis indicate that most of Asia experience strong seasonality in water supply and demand, which causes severe water stress during the course of a year, and highlight the need for better planning of water management with season-specific solutions, such as changes in irrigation practices and reservoir operation.

Furthermore, our basin scale hydro-economic analysis shows that South and East Asian basins have the highest hydro-climatic complexity, with lower coping capacity in South Asian basins. Although coping capacity is expected to improve in all basins, eight basins remain classified in the most vulnerable HE4 class (high water complexity combined with low economic strength) in the 2050s, with large populations living under severe water stress. These regions, in particular, will need effective solutions and better water management, in order to overcome critical water challenges. Increases in the coping capacity indicate the potential of Asia to achieve this, if resources are appropriately allocated.

As a strategic planning method to explore possible futures, our scenario-based approach provides useful insights, particularly with respect to the scale of socioeconomic impacts on water stress, and highlights a clear need for further work on managing water demands and identifying water policy interventions. Assessments of this type can benefit from improvements in some areas, particularly: socioeconomic impacts on the agriculture sector; the sophistication of water demand models and socioeconomic scenarios; and the reduction of uncertainty between GHMs. Nonetheless, our analysis, as the first water assessment of Asia in conjunction with SSPs and RCPs, highlights an urgent need to address water challenges, particularly in the identified hotspots and on the socioeconomic demand side, underlining the importance of targeted solutions for people.

Acknowledgements

The Water Futures and Solutions Initiative (WFaS) was launched by IIASA, UNESCO/UN-Water, the World Water Council (WWC), the International Water Association (IWA), and the Ministry of Land, Infrastructure and Transport (MOLIT) of the Republic of Korea, and has been supported by the government of Norway, the Asian Development Bank (ADB), and the Austrian Development Agency (ADA). More than 35 organizations contribute to the scientific project team, and an additional 25 organizations are represented in stakeholder groups. Furthermore, WFaS relies on numerous databases compiled and made available by many more organizations, which are referred to in this paper. The research described in this paper would not have been possible without the collaboration of all of these organizations in the WFaS Project Team. Y. Wada is supported by Japan Society for the Promotion of Science (JSPS) Oversea Research Fellowship (grant no. JSPS-2014-878). The WFaS data are available upon request.

References

Alcamo, J., M. Flörke, and M. Märker (2007), Future long-term changes in global water resources driven by socio-economic and climatic changes, Hydrological Sciences Journal, 52(2), 247-275, doi: 10.1623/hysj.52.2.247.

Arnell, N. (2004), Climate change and global water resources: SRES emissions and socio-economic scenarios, Global Environmental Change, 14(1), 31-52, doi: 10.1016/j.gloenvcha.2003.10.006.

Arnell, N., and B. Lloyd-Hughes (2014), The global-scale impacts of climate change on water resources and flooding under new climate and socio-economic scenarios, Climatic Change, 122(1), 127-140, doi: 10.1007/s10584-013-0948-4.

Arnell, N., et al. (2016), The impacts of climate change across the globe: A multi-sectoral assessment, Climatic Change, 134(3), 457-474, doi: 10.1007/s10584-014-1281-2.

Asian Development Bank (2013), Asian Water Development Outlook 2013: Measuring water security in Asia and the Pacific, Asian Development Bank, Mandaluyong City.

Asian Development Bank (2016), Asian Water Development Outlook 2016: Strengthening water security in Asia and the Pacific, Asian Development Bank, Mandaluyong City.

Bijl, D. L., P. W. Bogaart, T. Kram, B. J. M. de Vries, and D. P. van Vuuren (2016), Long-term water demand for electricity, industry and households, Environmental Science & Policy, 55, Part 1, 75-86, doi: 10.1016/j.envsci.2015.09.005.

Döll, P., H. Müller Schmied, C. Schuh, F. T. Portmann, and A. Eicker (2014), Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modeling with information from well observations and GRACE satellites, Water Resources Research, 50(7), 5698-5720, doi: 10.1002/2014WR015595.

Eisner, S., et al. (2017), An ensemble analysis of climate change impacts on streamflow seasonality across 11 large river basins, Climatic Change, 141(3), 401-417, doi: 10.1007/s10584-016-1844-5.

Falkenmark, M. (1997), Meeting water requirements of an expanding world population, Philosophical Transactions of the Royal Society B: Biological Sciences, 352(1356), 929-936, doi: 10.1098/rstb.1997.0072.

Falkenmark, M., J. Lundqvist, and C. Widstrand (1989), Macro‐scale water scarcity requires micro‐scale approaches, Natural resources forum, 13(4), doi: 10.1111/j.1477-8947.1989.tb00348.x.

Famiglietti, J. S., M. Lo, S. L. Ho, J. Bethune, K. J. Anderson, T. H. Syed, S. C. Swenson, C. R. de Linage, and M. Rodell (2011), Satellites measure recent rates of groundwater depletion in California's Central Valley, Geophysical Research Letters, 38(3), n/a-n/a, doi: 10.1029/2010GL046442.

Flörke, M., E. Kynast, I. Bärlund, S. Eisner, F. Wimmer, and J. Alcamo (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, 23(1), 144-156, doi: 10.1016/j.gloenvcha.2012.10.018.

Fricko, O., S. C. Parkinson, N. Johnson, M. Strubegger, M. T. H. v. Vliet, and K. Riahi (2016), Energy sector water use implications of a 2 °C climate policy, Environmental Research Letters, 11(3), 034011, doi: 10.1088/1748-9326/11/3/034011.

Gosling, S. N., and N. W. Arnell (2016), A global assessment of the impact of climate change on water scarcity, Climatic Change, 134(3), 371-385, doi: 10.1007/s10584-013-0853-x.

Grey, D., D. Garrick, D. Blackmore, J. Kelman, M. Muller, and C. Sadoff (2013), Water security in one blue planet: twenty-first century policy challenges for science, Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 371(2002), 20120406.

Haddeland, I., et al. (2011), Multimodel Estimate of the Global Terrestrial Water Balance: Setup and First Results, Journal of Hydrometeorology, 12(5), 869-884, doi: 10.1175/2011jhm1324.1.

Hall, J. W., D. Grey, D. Garrick, F. Fung, C. Brown, S. J. Dadson, and C. W. Sadoff (2014), Coping with the curse of freshwater variability, Science, 346(6208), 429-430, doi: 10.1126/science.1257890.

Hanasaki, N., S. Kanae, T. Oki, K. Masuda, K. Motoya, N. Shirakawa, Y. Shen, and K. Tanaka (2008a), An integrated model for the assessment of global water resources – Part 1: Model description and input meteorological forcing, Hydrology and Earth System Sciences, 12(4), 1007-1025, doi: 10.5194/hess-12-1007-2008.

Hanasaki, N., S. Kanae, T. Oki, K. Masuda, K. Motoya, N. Shirakawa, Y. Shen, and K. Tanaka (2008b), An integrated model for the assessment of global water resources – Part 2: Applications and assessments, Hydrology and Earth System Sciences, 12(4), 1027-1037, doi: 10.5194/hess-12-1027-2008.

Hanasaki, N., et al. (2013a), A global water scarcity assessment under Shared Socio-economic Pathways – Part 2: Water availability and scarcity, Hydrology and Earth System Sciences, 17(7), 2393-2413, doi: 10.5194/hess-17-2393-2013.

Hanasaki, N., et al. (2013b), A global water scarcity assessment under Shared Socio-economic Pathways – Part 1: Water use, Hydrology and Earth System Sciences, 17(7), 2375-2391, doi: 10.5194/hess-17-2375-2013.

Hayashi, A., K. Akimoto, T. Homma, K. Wada, and T. Tomoda (2014), Change in the Annual Water Withdrawal-to-Availability Ratio and Its Major Causes: An Evaluation for Asian River Basins Under Socioeconomic Development and Climate Change Scenarios, Energy and Environment Research, 4(2), doi: 10.5539/eer.v4n2p34.

Hempel, S., K. Frieler, L. Warszawski, J. Schewe, and F. Piontek (2013), A trend-preserving bias correction - the ISI-MIP approach, Earth Syst. Dynam., 4(2), 219-236, doi: 10.5194/esd-4-219-2013.

Hijioka, Y., E. Lin, J. J. Pereira, R. T. Corlett, X. Cui, G. E. Insarov, R. D. Lasco, E. Lindgren, and A. Surjan (2014), Asia, in Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change, edited by V. R. Barros, et al., pp. 1327-1370, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Immerzeel, W., and M. Bierkens (2012), Asia's water balance, Nature Geoscience, 5(12), 841-842, doi: 10.1038/ngeo1643.

Immerzeel, W., L. P. H. van Beek, and M. F. P. Bierkens (2010), Climate Change Will Affect the Asian Water Towers, Science, 328(5984), 1382-1385, doi: 10.1126/science.1183188.

IPCC (2012), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)], Cambridge, UK, and New York, NY, USA.

Jalava, M., J. H. A. Guillaume, M. Kummu, M. Porkka, S. Siebert, and O. Varis (2016), Diet change and food loss reduction: What is their combined impact on global water use and scarcity?, Earth's Future, 4(3), 62-78, doi: 10.1002/2015EF000327.

Jones, B., and B. C. O'Neill (2016), Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways, Environmental Research Letters, 11(8), 084003, doi: 10.1088/1748-9326/11/8/084003.

Kahil, M. T., A. Dinar, and J. Albiac (2015a), Modeling water scarcity and droughts for policy adaptation to climate change in arid and semiarid regions, Journal of Hydrology, 522, 95-109, doi: 10.1016/j.jhydrol.2014.12.042.

Kahil, M. T., J. D. Connor, and J. Albiac (2015b), Efficient water management policies for irrigation adaptation to climate change in Southern Europe, Ecological Economics, 120, 226-233, doi: 10.1016/j.ecolecon.2015.11.004.

Kiguchi, M., Y. Shen, S. Kanae, and T. Oki (2015), Re-evaluation of future water stress due to socio-economic and climate factors under a warming climate, Hydrological Sciences Journal, 60(1), 14-29, doi: 10.1080/02626667.2014.888067.

Lehner, B., et al. (2011), High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management, Frontiers in Ecology and the Environment, 9(9), 494-502, doi: 10.1890/100125.

Malsy, M., T. Aus der Beek, S. Eisner, and M. Flörke (2012), Climate change impacts on Central Asian water resources, Advances in Geosciences, 32, 77-83, doi: 10.5194/adgeo-32-77-2012.

Masaki, Y., N. Hanasaki, H. Biemans, H. M. Schmied, Q. Tang, Y. Wada, S. Gosling, K. Takahashi, and Y. Hijioka (2017), Intercomparison of global river discharge simulations focusing on dam operation --- Part II: Multiple models analysis in two case-study river basins, Missouri-Mississippi and Green-Colorado, Environmental Research Letters, In press, doi: 10.1088/1748-9326/aa57a8.

McGuire, V. L. (2011), Water-level changes in the High Plains aquifer, predevelopment to 2009, 2007-08, and 2008-09, and change in water in storage, predevelopment to 2009, *Report Rep. 2011-5089*, Reston, VA.

O'Neill, B. C., E. Kriegler, K. Riahi, K. L. Ebi, S. Hallegatte, T. R. Carter, R. Mathur, and D. P. van Vuuren (2013), A new scenario framework for climate change research: the concept of shared socioeconomic pathways, Climatic Change, 122(3), 387-400, doi: 10.1007/s10584-013-0905-2.

Oki, T., Y. Agata, S. Kanae, T. Saruhashi, D. Yang, and K. Musiake (2001), Global assessment of current water resources using total runoff integrating pathways, Hydrological Sciences Journal, 46(6), 983-995, doi: 10.1080/02626660109492890.

Prudhomme, C., et al. (2014), Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment, Proceedings of the National Academy of Sciences, 111(9), 3262-3267, doi: 10.1073/pnas.1222473110.

Raskin, P., P. Gleick, P. Kirshen, G. Pontius, and K. Strzepek (1997), Water futures: Assessment of long-range patterns and problems. Comprehensive assessment of the freshwater resources of the world, Stockholm Environment Institute, Stockholm.

Rijsberman, F. R. (2006), Water scarcity: fact or fiction?, Agricultural water management, 80(1), 5-22, doi: 10.1016/j.agwat.2005.07.001.

Sadoff, C. W., et al. (2015), Securing Water, Sustaining Growth: Report of the GWP/OECD Task Force on Water Security and Sustainable Growth, University of Oxford, Oxford.

Samaniego, L., et al. (2017), Propagation of forcing and model uncertainties on to hydrological drought characteristics in a multi-model century-long experiment in large river basins, Climatic Change, 141(3), 435-449, doi: 10.1007/s10584-016-1778-y.

Scanlon, B. R., C. C. Faunt, L. Longuevergne, R. C. Reedy, W. M. Alley, V. L. McGuire, and P. B. McMahon (2012), Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley, Proceedings of the National Academy of Sciences, 109(24), 9320-9325, doi: 10.1073/pnas.1200311109.

Schewe, J., et al. (2014), Multimodel assessment of water scarcity under climate change, Proc Natl Acad Sci U S A, 111(9), 3245-3250, doi: 10.1073/pnas.1222460110.

Schmied, H. M., S. Eisner, D. Franz, M. Wattenbach, F. T. Portmann, M. Flörke, and P. Döll (2014), Sensitivity of simulated global-scale freshwater fluxes and storages to input data, hydrological model structure, human water use and calibration, Hydrology and Earth System Sciences, 18(9), 3511-3538, doi: 10.5194/hess-18-3511-2014.

Shiklomanov, I. A. (2000), Appraisal and Assessment of World Water Resources, Water International, 25(1), 11-32, doi: 10.1080/02508060008686794.

Van Beek, L., Y. Wada, and M. F. Bierkens (2011), Global monthly water stress: 1. Water balance and water availability, Water Resources Research, 47(7), doi: 10.1029/2010WR009792.

Veldkamp, T. I., Y. Wada, H. de Moel, M. Kummu, S. Eisner, J. C. Aerts, and P. J. Ward (2015), Changing mechanism of global water scarcity events: Impacts of socioeconomic changes and inter-annual hydro-climatic variability, Global Environmental Change, 32, 18-29, doi: 10.1016/j.gloenvcha.2015.02.011.

Vörösmarty, C. J., C. Leveque, and C. Revenga (2005), Millennium Ecosystem Assessment Volume 1: Conditions and Trends, chap. 7: Freshwater ecosystems, 207 ed., Washington DC.

Vörösmarty, C. J., P. Green, J. Salisbury, and R. B. Lammers (2000), Global Water Resources: Vulnerability from Climate Change and Population Growth, Science, 289(5477), 284-288, doi: 10.1126/science.289.5477.284.

Wada, Y., and M. F. P. Bierkens (2014), Sustainability of global water use: past reconstruction and future projections, Environmental Research Letters, 9(10), 104003, doi: 10.1088/1748-9326/9/10/104003.

Wada, Y., L. Van Beek, and M. F. Bierkens (2011a), Modelling global water stress of the recent past: on the relative importance of trends in water demand and climate variability, Hydrology and Earth System Sciences, 15(12), 3785-3808, doi: 10.5194/hess-15-3785-2011.

Wada, Y., D. Wisser, and M. F. P. Bierkens (2014a), Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources, Earth System Dynamics, 5(1), 15-40, doi: 10.5194/esd-5-15-2014.

Wada, Y., T. Gleeson, and L. Esnault (2014b), Wedge approach to water stress, Nature Geoscience, 7(9), 615-617, doi: 10.1038/ngeo2241.

Wada, Y., L. P. H. van Beek, N. Wanders, and M. F. P. Bierkens (2013a), Human water consumption intensifies hydrological drought worldwide, Environmental Research Letters, 8(3), 034036, doi: 10.1088/1748-9326/8/3/034036.

Wada, Y., L. Van Beek, D. Viviroli, H. H. Dürr, R. Weingartner, and M. F. Bierkens (2011b), Global monthly water stress: 2. Water demand and severity of water stress, Water Resources Research, 47(7), doi: 10.1029/2010WR009791.

Wada, Y., et al. (2013b), Multimodel projections and uncertainties of irrigation water demand under climate change, Geophysical Research Letters, 40(17), 4626-4632, doi: 10.1002/grl.50686.

Wada, Y., et al. (2016), Modeling global water use for the 21st century: the Water Futures and Solutions (WFaS) initiative and its approaches, Geoscientific Model Development, 9(1), 175-222, doi: 10.5194/gmd-9-175-2016.

Wanders, N., and Y. Wada (2015), Human and climate impacts on the 21st century hydrological drought, Journal of Hydrology, 526, 208-220, doi: 10.1016/j.jhydrol.2014.10.047.

Warszawski, L., K. Frieler, V. Huber, F. Piontek, O. Serdeczny, and J. Schewe (2014), The inter-sectoral impact model intercomparison project (ISI–MIP): project framework, Proceedings of the National Academy of Sciences, 111(9), 3228-3232, doi: 10.1073/pnas.1312330110.

World Bank (2016), High and Dry : Climate Change, Water, and the Economy, World Bank Group, Washington, D.C.

Appendix A

A1. Hydro-Economic (HE) classification system

The Hydro-Economic classification system is a method to assess water security of countries or basins based on two dimensions, hydro-climatic complexity, and economic-institutional capacity. Hydro-climatic complexity (x-axis) represents challenges related to water resources, and economic-institutional capacity (y-axis) indicates a capacity to cope with water resource problems. In this study, the integrated hydro-climatic complexity index is determined using four sub-indicators: 1) Total renewable water resources per capita, 2) water use intensity, 3) variability of monthly runoff, and 4) dependency ratio of external to total renewable water resources. Economic-institutional capacity index is approximated by means of one sub-indicator, GDP per capita. The calculation of the hydro-climatic complexity and economic-institutional capacity indexes is completed as follows:

1) For each sub-indicator, five generic classes are defined, including 'very low', 'low', 'medium', 'high', and 'very high'.

2) For each sub-indicator v_i, a normalized sub-indicator value X_i is calculated as follows:

a. The interval (broad class) $v_i \in [V_j, V_{j+1}]$ into which the sub-indicator value v_i of a country/region falls is determined.

b. The normalized sub-indicator value $X_i(v_i)$ is calculated using the following equation:

$$X_i(v_i) = X_i(V_j) + \max(0, \min(1, \frac{v_i - V_j}{V_{j+1} - V_j}))(X_i(V_{j+1}) - X_i(V_j)) \quad (1)$$

If v_i is larger (smaller) than maximum (minimum) of the range for the five classes, $X_i(v_i)$ is defined as 1 (0). (In the case of sub-indicator 1, 1 and 0 are opposite).

3) Finally, the integrated index I is calculated as the weighted sum of normalized sub-indicators X_i.

$$I = \sum_{i=1}^{n} w_i X_i(v_i) \,/\, \sum_{i=1}^{n} w_i$$

(2)

Where $X_i(v_i)$ is each normalized sub-indicator for each country/region. The parameter w_i is weight according to a few classes of perceived importance of the sub-indicators. Different weights have been assigned to the different sub-indicators (2 for sub-indicator 1, 2 for sub-indicator 2, and 1 for sub-indicator 3).

A detailed description of each sub-indicator is provided subsequently:

1. Hydro-climatic complexity index (x-axis)

Sub-indicator 1: Total renewable water resources per capita

Total renewable water resources per capita (TWRC, [m^3/cap/yr]) is calculated by adding a region's internal renewable water resources and the inflow from upstream regions. This study uses ten year period average of a multi-model ensemble of three GHMs and five GCMs to estimate available surface water resources for each decade. The sub-indicator is normalized using the five classes defined in Table A1:

(Insert Table A1)

Sub-indicator 2: Water use intensity

The ratio of total water demand for irrigation, industrial and domestic water use (TWD, [m^3/yr]) to total renewable water resources (TWR, [m^3/yr]) is used as a proxy of water use intensity. The multi-model ensemble mean have been used to estimate TWD and TWR. The sub-indicator is normalized using the five classes defined in Table A2:

(Insert Table A2)

Sub-indicator 3: Variability of monthly runoff

The variability of water supply is evaluated by using the coefficient of variance (standard deviation divided by mean) of monthly runoff based on ten year time series (CV, [%]). This coefficient of variance includes both sub-annual and interannual variability, but the sub-annual variability tends to be dominant over the monsoon region. The sub-indicator is normalized using the five classes defined in Table A3.

(Insert Table A3)

Sub-indicator 4: Dependency ratio of external to total renewable water resource

Sub-indicator 4 is the ratio of external water resources to the total renewable resource (DPC [-]).This sub- indicator is normalized using the five classes defined in Table A4.

(Insert Table A4)

2. Economic-institutional capacity index (y-axis)

Sub-indicator 1: GDP per capita

GDP per capita (GDPC [US$/cap/yr]) is used as a proxy of economic-institutional capacity. Both GDP and population are provided in the SSP scenarios. This sub-indicator is normalized using the five classes defined in Table A5.

(Insert Table A5)

A2. Regional description of seasonal change in water stress

The analysis of seasonal water stress indicates that there are two groups with different characteristics related to seasonality. The first group includes regions that experience severe water stress conditions only in some seasons. For instance, the eastern part of south China and east Australia face the most severe water stress conditions during SON and DJF. DJF is peak season of water stress in the eastern part of central India, Bangladesh, central China and the western part of South China. The highest water stress season in western part of central

India is MAM while northern India faces severe and prolonged water stress throughout the year except during JJA. In Thailand severe water stress occurs in DJF and MAM whilst for Java island of Indonesia severe stress conditions occur in JJA, and to a lesser extent in DJF and MAM. The west Asian region covering areas from Afghanistan to Uzbekistan experiences water stress for three seasons from MAM through to SON, most severely in JJA. The second group includes large areas that face severe water stress conditions throughout the year such as areas of Pakistan and west India, south India excluding its east coast, northwest and northeast China, some parts of north China, and the north of east China. However, they also experience seasonal severe water stress conditions. For instance, MAM is the worst for Pakistan, west India, parts of north China and the north of east China, all of which are particularly serious hotspot regions.

One key driver of seasonally severe water stress in Asia is high irrigation demand during dry season. High irrigation and consequent severe stress occur during DJF and MAM in the areas over Pakistan and west India, south India, northeast China, the areas covering north China and the northern part of east China and Thailand, during DJF in the eastern part of south China and Bangladesh, during MAM in the western part of central India, and during JJA in the areas from Afghanistan to Uzbekistan and Java island. Severe water stress conditions can also occur during the wet season due to high demand in the areas over Pakistan, west India and south India during JJA; in the eastern part of south China, Bangladesh, and the western part of central India during SON; and in north India during MAM and SON. However, reductions in severe water stress conditions are expected to take place in the 2050s in west India and Japan in all seasons; central India during MAM; Myanmar and Thai during SON and DJF; a part of south China during SON; and part of east Australia from MAM to SON.

A3. The methodology of the attribution analysis for increases in water stress

It is expected that the level of water stress will change in the future compared with that of the 2010s. Changes in water stress (determined by WTA) are driven by either an increase in water demand, a decrease in water supply, or both of them. This study estimates an attribution rate (AR) to the increase in water stress at grid scale using the equations described subsequently.

For each grid cell, let i be a set of water supply and demand components, where $i = (1,\ldots, 5)$. Water supply components (i = 1, 2) include runoff and inflow, respectively, and water demand components (i = 3, 4, 5) include irrigation, industrial and municipal water demands, respectively. $A_{i,t}$ is the value of each component i that can contribute to changes in water stress in each time step t. We calculate the change in the value of each component i, $\Delta A_{i,t}$, between time steps t and t_0, as shown in equation (3):

$$\Delta A_{i,t} = A_{i,t} - A_{i,t_0} \tag{3}$$

Then in equation (4), we calculate the contribution of each component i, $AA_{i,t}$, to water stress as the absolute value of the change in the value of that component between time steps, $\Delta A_{i,t}$, if supply decreases and/or demand increases. Otherwise, $AA_{i,t}$ is equal to zero.

$$AA_{i,t} = \begin{cases} |\Delta A_{i,t}| & (\Delta A_{i,t} < 0, \quad i = 1,2) \\ |\Delta A_{i,t}| & (\Delta A_{i,t} > 0, \quad i = 3,4,5) \\ 0 & (\quad otherwise \quad) \end{cases} \tag{4}$$

Finally, we calculate the attribution rate of each component i, $AR_{i,t}$, which is equal to the absolute contribution of each component divided by the sum of the contribution of all components, as shown in equation (5):

$$AR_{i,t} = {AA_{i,t}} \Big/ {\sum_{i=1}^{5} AA_{i,t}} \tag{5}$$

Appendix B

(Insert Table B1)

(Insert Table B2)

(Insert Table B3)

(Insert Table B4)

(Insert Table B5)

(Insert Figure B1)

(Insert Figure B2)

(Insert Figure B3)

(Insert Figure B4)

Table legends

Table 1: Total water demand at country level [km^3/year]

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Table B1: Scenario assumptions for technology and structural change in the industry and domestic sector

Table B2: Per capita available surface water resources at country level [m3/capita/year]

Table B3: Irrigation water demand [km^3/year]

Table B4: Industrial water demand [km^3/year]

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Figure legends

Figure 1: Methodological framework of the Water Future and Solutions initiative fast track. (RCPs: Representative Concentration Pathways, SSPs: Shared Socioeconomic Pathways, GCMs: Global Climate Models, IAMs: Integrated Assessment Models, WFaS: Water Future and Solutions, HE: Hydro-economic classification).

Figure 2: (a) Yearly average available surface water resources [Million m^3/yr] (b) Available surface water resources in the driest month [Million m^3/yr], (c) Yearly average available surface water resources per capita [m^3/yr/cap], (d) Available surface water resources per capita in the driest month [m^3/yr/cap].

Figure 3: Water demand in the 2010s and change between the 2010s and the 2050s for each scenario [Million m3/yr]. Water demand is the total of irrigation, industrial and municipal water demand.

Figure 4: Withdrawal to availability ratio (WTA): (a) historical value in the 2010s; (b) changes in the WTA in the 2050s compared with the 2010s for each scenario; (c) decadal consistency of trend during the 2010s to the 2050s. In Figure 4c, blue and red are consistent increase and decrease throughout the period, respectively. Orange indicates decrease in three decades and increase in a decade. Light blue is opposite.

Figure 5: (a) The seasonal water scarcity index in the 2010s. (b) Change in the seasonal water scarcity index between the 2010s and the 2050s in the Middle of the Road scenario. (DJF: December-January-February, MAM: March-April-May, JJA: June-July-August, and SON: September-October-November).

Figure 6: Attribution ratio to increases in the WTA score for: (a) Supply side, and (b) Demand side. A value of attribution rate of a factor equals to 0 indicates no impact of that factor on water scarcity, while a value of 1 indicates that water scarcity is totally driven by that factor.

Figure 7: Results of basin scale hydro-economic analysis in the Middle of the Road scenario. (a) Hydro-economic class in the 2050s. (b) Map of selected 20 Asian major basins. (c) Changes in the hydro-economic classification of basins over time. (c1) the integrated HE index; (c2) sub-index 1 of per capita available surface water resources; (c3) sub-index 2 of

water use intensity; (c4) sub-index 3 of monthly variability of runoff (seasonality). Index 4 of external dependency is not included because this index is zero in a basin-scale analysis. Colors indicate different Asian sub-regions.

Figure B1: Decadal consistence of change in available surface water resources during the 2020s-2050s compared to 2010s. Blue and red are consistent increase and decrease throughout the period, respectively. Orange indicates decrease in three decades and increase in one decade. Light blue is opposite.

Figure B2: (a) Change in inflow for each grid between the 2010s and 2050s [Million m3/yr], and (b) attribution ratio of inflow to increases of the WTA score in the 2050s.

Figure B3: Consistency of change in water scarcity for each season during the 2020s to the 2050s compared with the 2010s under the Middle of the Road scenario. The number of "+" and "-" in the color bar indicates the number of decade with increase and decrease in score of withdrawal to availability ratio (WTA). For instance, dark red shows a consistent increase in the score through four decades, and orange indicates that only one decade gives a lower score but rest of decades face higher score of WTA.

Figure B4: Shifts of Asian basins in the HE dimension in the Middle of the Road scenario. The x- and y-axes indicate the integrated HE index of the hydro-climatic complexity and the economic-institutional capacity, respectively. This figure is similar to Figure 7c1 but for all 40 basins. Because GDP per capita will grow in all basins, all basins shift upward in the HE dimension. Each marker in a plot is about year 2000, 2010, 2030 and 2050. Colors indicate different Asian sub-regions.

Table 1. Total water demand at country level [km^3/year].

		Sustainability			Middle of the Road			Regional Rivalry		
		2010	**2030**	**2050**	**2010**	**2030**	**2050**	**2010**	**2030**	**2050**
Advanced economies	Australia	33	35	36	33	35	37	33	36	38
	Singapore	0.8	1.4	1.6	0.9	1.7	2.3	0.9	1.7	2.4
	New Zealand	4.0	4.2	4.6	4.1	4.5	4.5	4.1	4.7	4.8
	Republic of Korea	29	32	31	29	36	34	29	34	32
	Brunei Darussalam	0.3	0.2	0.1	0.3	0.3	0.4	0.3	0.3	0.4
	Japan	67	61	60	68	65	64	68	66	65
	SUM	134	134	133	135	143	143	135	143	143
East Asia	China	846	1142	1271	850	1207	1335	848	1243	1397
	Mongolia	1.0	1.5	1.9	1.0	1.7	2.5	1.0	1.9	2.8
	SUM	847	1143	1273	850	1209	1337	849	1245	1400
Central and West Asia	Uzbekistan	64	74	87	64	76	82	64	76	88
	Afghanistan	52	55	60	51	54	59	51	54	59
	Kyrgyzstan	12	13	14	12	13	14	12	13	15
	Georgia	3	6	8	3	6	8	3	6	9
	Turkmenistan	25	29	30	25	32	36	25	31	34
	Armenia	3	4	6	3	5	5	3	5	6
	Tajikistan	10	11	14	10	12	13	10	12	14
	Kazakhstan	29	34	34	31	39	41	30	38	39
	Azerbaijan	17.7	18.6	18.5	19.0	22.0	19.8	18.4	21.2	21.1
	SUM	217	245	271	219	259	278	217	257	284
Southeast Asia	LPDR	3.6	4.7	5.8	3.6	4.8	5.8	3.6	4.9	6.2
	Viet Nam	56	62	66	57	65	70	57	68	75
	Myanmar	24.8	24.8	25.7	24.7	25.4	25.7	24.7	25.5	26.1
	Malaysia	10.8	11.8	12.4	11.1	14.0	16.8	11.2	15.1	18.9
	Thailand	64	69	73	64	72	77	64	73	78
	Philippines	29	31	40	30	35	43	29	36	49
	Indonesia	91	103	107	91	112	120	91	115	127
	Cambodia	4.0	4.2	5.0	4.0	4.3	5.0	4.0	4.3	4.8
	SUM	283	310	336	285	332	364	285	341	385
Pacific	Tonga	0.002	0.001	0.000	0.002	0.002	0.003	0.002	0.003	0.003
	Papua New Guinea	0.3	0.4	0.8	0.3	0.5	0.8	0.3	0.6	0.9
	Vanuatu	0.002	0.001	0.000	0.002	0.002	0.002	0.002	0.003	0.003
	Samoa	0.002	0.002	0.000	0.002	0.004	0.004	0.002	0.004	0.004
	Solomon Islands	0.005	0.006	0.014	0.005	0.008	0.012	0.005	0.009	0.016
	Timor-Leste	0.10	0.11	0.21	0.10	0.11	0.12	0.09	0.11	0.15
	Fiji	0.04	0.05	0.07	0.04	0.06	0.08	0.04	0.07	0.09
	SUM	0.5	0.6	1.1	0.5	0.7	1.0	0.5	0.8	1.2
South Asia	Pakistan	314	322	335	316	318	341	316	321	349
	Maldives	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Bangladesh	57	64	72	58	65	74	58	65	74
	Bhutan	0.7	0.8	0.9	0.7	0.8	0.9	0.7	0.8	0.9
	Nepal	9.3	10.1	11.8	9.3	10.0	11.7	9.3	10.0	11.2
	India	914	1017	1093	913	1030	1117	912	1045	1171
	Sri Lanka	11	12	13	11	13	15	11	13	14
	SUM	1306	1427	1525	1307	1437	1559	1307	1455	1620
Asia SUM		2787	3260	3539	2797	3381	3683	2794	3442	3833

Table 2. Changes in the number of people under severe water stress at country level [Millions] *.

		Sustainability			Middle of the Road			Regional Rivalry		
		2010	**2030**	**2050**	**2010**	**2030**	**2050**	**2010**	**2030**	**2050**
East Asia	China	482 (35%)	602 (43%)	572 (46%)	468 (34%)	598 (42%)	608 (47%)	468 (34%)	605 (42%)	629 (47%)
	Mongolia	0.02 (1%)	0.0 (1%)	0.3 (9%)	0.02 (1%)	0.4 (11%)	0.7 (19%)	0.02 (1%)	0.4 (10%)	0.8 (19%)
	SUM	482 (35%)	602 (43%)	572 (45%)	468 (34%)	599 (42%)	609 (47%)	468 (34%)	605 (42%)	629 (47%)
South Asia	Bangladesh	15 (10%)	26 (15%)	46 (26%)	15 (10%)	27 (15%)	48 (25%)	15 (10%)	29 (16%)	51 (24%)
	Bhutan	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
	India	407 (33%)	521 (36%)	611 (39%)	394 (32%)	545 (35%)	708 (41%)	394 (32%)	589 (37%)	802 (40%)
	Maldives	0.2 (6%)	0.2 (6%)	0.2 (5%)	0.2 (6%)	0.2 (6%)	0.3 (6%)	0.2 (6%)	0.2 (6%)	0.3 (6%)
	Nepal	3 (11%)	4 (11%)	5 (12%)	2 (6%)	4 (11%)	5 (12%)	2 (6%)	5 (11%)	7 (12%)
	Sri Lanka	1.4 (7%)	1.3 (6%)	1.2 (6%)	1.2 (6%)	1.4 (6%)	1.4 (6%)	1.2 (6%)	1.4 (6%)	1.6 (6%)
	Pakistan	82 (48%)	115 (52%)	129 (52%)	81 (47%)	113 (48%)	151 (53%)	81 (47%)	126 (50%)	180 (53%)
	SUM	509 (32%)	668 (35%)	792 (39%)	493 (31%)	691 (34%)	913 (40%)	493 (31%)	750 (35%)	1042 (40%)
Southeast Asia	Cambodia	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
	Indonesia	34 (14%)	69 (26%)	73 (27%)	34 (14%)	68 (25%)	98 (34%)	34 (14%)	71 (25%)	97 (32%)
	Lao PDR	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
	Malaysia	0.1 (0%)	0.1 (0%)	0.1 (0%)	0.1 (0%)	0.1 (0%)	9 (21%)	0.1 (0%)	0.1 (0%)	9 (20%)
	Myanmar	0.12 (0%)	0.11 (0%)	0.09 (0%)	0.12 (0%)	0.12 (0%)	0.11 (0%)	0.12 (0%)	0.13 (0%)	0.13 (0%)
	Philippines	17 (18%)	21 (18%)	34 (25%)	17 (18%)	29 (23%)	35 (23%)	17 (18%)	29 (22%)	36 (21%)
	Thailand	7 (10%)	8 (10%)	8 (12%)	7 (10%)	8 (11%)	8 (11%)	7 (10%)	8 (10%)	8 (10%)
	Viet Nam	7 (8%)	8 (8%)	11 (12%)	7 (8%)	8 (8%)	12 (12%)	7 (8%)	8 (8%)	13 (12%)
	SUM	65 (11%)	106 (16%)	127 (19%)	65 (11%)	114 (16%)	162 (22%)	65 (11%)	117 (16%)	164 (20%)
Central and West Asia	Afghanistan	12 (38%)	21 (43%)	33 (54%)	12 (36%)	22 (41%)	41 (54%)	12 (36%)	24 (41%)	49 (53%)
	Kazakhstan	4 (22%)	6 (32%)	7 (34%)	4 (22%)	7 (34%)	8 (36%)	4 (22%)	7 (33%)	8 (34%)
	Kyrgyzstan	3 (54%)	4 (56%)	4 (59%)	3 (54%)	4 (55%)	4 (57%)	3 (54%)	4 (54%)	5 (54%)
	Tajikistan	2 (24%)	2 (24%)	2 (26%)	1 (22%)	2 (24%)	2 (23%)	1 (22%)	2 (24%)	2 (23%)
	Turkmenistan	2 (42%)	3 (44%)	3 (49%)	2 (41%)	3 (46%)	4 (53%)	2 (41%)	3 (45%)	4 (51%)
	Uzbekistan	16 (62%)	19 (66%)	19 (68%)	16 (62%)	19 (63%)	20 (64%)	16 (62%)	20 (62%)	23 (65%)
	Armenia	1 (35%)	2 (73%)	2 (76%)	1 (35%)	2 (71%)	2 (73%)	1 (35%)	2 (70%)	2 (70%)
	Azerbaijan	4 (43%)	5 (45%)	5 (49%)	4 (43%)	5 (51%)	5 (45%)	4 (43%)	5 (50%)	5 (48%)
	Georgia	0 (0%)	0.20 (5%)	0.17 (5%)	0 (0%)	0.20 (5%)	0.17 (5%)	0 (0%)	0.21 (5%)	1.54 (37%)
	SUM	44 (40%)	62 (46%)	75 (52%)	43 (39%)	64 (45%)	85 (51%)	43 (39%)	67 (45%)	101 (51%)
Advanced economies	Australia	2 (8%)	2 (8%)	10 (26%)	2 (8%)	2 (8%)	9 (26%)	2 (8%)	2 (8%)	7 (26%)
	Brunei Darussalam	0.01 (1%)	0.01 (1%)	0.01 (1%)	0.01 (1%)	0.01 (1%)	0.01 (1%)	0.01 (1%)	0.01 (1%)	0.01 (1%)
	Japan	25 (19%)	26 (22%)	26 (23%)	25 (19%)	25 (21%)	24 (22%)	25 (19%)	23 (20%)	19 (20%)
	New Zealand	0.02 (0%)	0.02 (0%)	0.02 (0%)	0.02 (0%)	0.02 (0%)	0.02 (0%)	0.02 (0%)	0.02 (0%)	0.02 (0%)
	Republic of Korea	24 (49%)	25 (49%)	24 (50%)	24 (49%)	25 (50%)	23 (50%)	24 (49%)	24 (50%)	21 (50%)
	Singapore	0 (0%)	0 (0%)	7 (92%)	0 (0%)	7 (90%)	7 (91%)	0 (0%)	7 (89%)	7 (89%)
	SUM	50 (24%)	54 (25%)	67 (32%)	50 (24%)	59 (28%)	64 (31%)	50 (24%)	56 (27%)	54 (30%)
Pacific	Tonga	0.02 (16%)	0.01 (14%)	0.01 (12%)	0.02 (16%)	0.02 (16%)	0.02 (15%)	0.02 (16%)	0.02 (16%)	0.02 (16%)
	Papua New Guinea	0.03 (0%)	0.04 (0%)	0.05 (0%)	0.03 (0%)	0.05 (0%)	0.06 (1%)	0.03 (0%)	0.05 (1%)	0.07 (1%)
	Vanuatu	0.04 (18%)	0.05 (16%)	0.05 (14%)	0.04 (18%)	0.06 (17%)	0.07 (16%)	0.04 (18%)	0.07 (18%)	0.10 (20%)
	Samoa	0.06 (31%)	0.07 (41%)	0.08 (54%)	0.06 (31%)	0.08 (41%)	0.09 (54%)	0.06 (31%)	0.08 (36%)	0.10 (39%)
	Solomon Islands	0.01 (3%)	0.02 (3%)	0.02 (2%)	0.01 (3%)	0.02 (3%)	0.02 (2%)	0.01 (3%)	0.02 (3%)	0.03 (2%)
	Timor-Leste	0.01 (1%)	0.01 (1%)	0.01 (0%)	0.01 (1%)	0.01 (1%)	0.01 (0%)	0.01 (1%)	0.01 (1%)	0.02 (1%)
	Fiji	0.03 (4%)	0.03 (3%)	0.03 (3%)	0.03 (4%)	0.03 (4%)	0.03 (3%)	0.03 (4%)	0.04 (4%)	0.04 (4%)
	SUM	0.21 (2%)	0.25 (2%)	0.25 (2%)	0.21 (2%)	0.27 (2%)	0.30 (2%)	0.21 (2%)	0.29 (2%)	0.38 (2%)
Asia total		1150 (30%)	1491 (34%)	1634 (38%)	1119 (29%)	1526 (34%)	1834 (39%)	1119 (29%)	1596 (34%)	1991 (39%)

*Between parentheses is the percentage of population exposed to severe water stress over total population.

Table A1: The classes for total renewable water resources per capita.

Class	Range of the sub-indicator	Range of the normalized indicator
Very high	$10000 \leq TWRC < 20000$	$0 \leq X < 0.2$
High	$10000 \leq TWRC < 20000$	$0.2 \leq X < 0.4$
Medium	$2000 \leq TWRC < 5000$	$0.4 \leq X < 0.6$
Low	$1000 \leq TWRC < 2000$	$0.6 \leq X < 0.8$
Very low	$100 \leq TWRC < 1000$	$0.8 \leq X < 1.0$

Table A2: The classes for water use intensity.

Class	Range of the sub-indicator	Range of the normalized indicator
Very Low	$0.01 \leq TWD/TWR < 0.05$	$0 \leq X < 0.2$
Low	$0.05 \leq TWD/TWR < 0.15$	$0.2 \leq X < 0.4$
Medium	$0.15 \leq TWD/TWR < 0.30$	$0.4 \leq X < 0.6$
High	$0.30 \leq TWD/TWR < 0.60$	$0.6 \leq X < 0.8$
Very high	$0.60 \leq TWD/TWR < 1.00$	$0.8 \leq X < 1.0$

Table A3: The classes for variability of monthly runoff.

Class	Range of the sub-indicator	Range of the normalized indicator
Very Low	$0 \leq CVTWR < 30$	$0 \leq X < 0.2$
Low	$30 \leq CVTWR < 60$	$0.2 \leq X < 0.4$
Medium	$60 \leq CVTWR < 100$	$0.4 \leq X < 0.6$
High	$100 \leq CVTWR < 150$	$0.6 \leq X < 0.8$
Very high	$150 \leq CVTWR < 225$	$0.8 \leq X < 1.0$

Table A4: The classes for dependency ratio of external to total renewable water resource.

Class	Range of the sub-indicator	Range of the normalized indicator
Very Low	$0.05 \leq DPC < 0.30$	$0 \leq X < 0.2$
Low	$0.30 \leq DPC < 0.45$	$0.2 \leq X < 0.4$
Medium	$0.45 \leq DPC < 0.55$	$0.4 \leq X < 0.6$
High	$0.55 \leq DPC < 0.70$	$0.6 \leq X < 0.8$
Very high	$0.70 \leq DPC < 0.95$	$0.8 \leq X < 1.0$

Table A5: The classes for GDP per capita.

Class	Range of the sub-indicator	Range of the normalized indicator
Very Low	$250 \leq GDPC < 3000$	$0 \leq X < 0.2$
Low	$3000 \leq GDPC < 10000$	$0.2 \leq X < 0.4$
Medium	$10000 \leq GDPC < 20000$	$0.4 \leq X < 0.6$
High	$20000 \leq GDPC < 35000$	$0.6 \leq X < 0.8$
Very high	$35000 \leq GDPC < 90000$	$0.8 \leq X < 1.0$

Table B1. Scenario assumptions for technology and structural change in the industry and domestic sector.

		Hydro-Economic (HE) classification[1]			
		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 change rate]	SSP1-SUQ	1.10%	1.10%	1.20%	1.10%
	SSP2-BAU	0.60%	1.00%	1.10%	1.00%
	SSP3-DIV	0.30%	0.60%	1.00%	0.60%
Structural change[2] [Cange in cooling system, i.e. fom one-through to tower cooling]	SSP1-SUQ	40yr	40yr	40yr	40yr
	SSP2-BAU	None	40yr	40yr	40yr
	SSP3-DIV	None	None	40yr	None
MANUFACTURING SECTOR					
Technological change [annual change rate]	SSP1-SUQ	1.10%	1.10%	1.20%	1.10%
	SSP2-BAU	0.60%	1.00%	1.10%	1.00%
	SSP3-DIV	0.30%	0.60%	1.00%	0.60%
Structual change [change in intensity over ver time relative to GDP per capita]	SSP1-SUQ	Yes	Yes	Yes	Yes
	SSP2-BAU	Yes	Yes	Yes	Yes
	SSP3-DIV	Yes	Yes	Yes	Yes
DOMSTIC SECTOR					
Technological cange [annual change rate]	SSP1-SUQ	1.10%	1.10%	1.20%	1.10%
	SSP2-BAU	0.60%	1.00%	1.10%	1.00%
	SSP3-DIV	0.30%	0.60%	1.00%	0.60%
Structural change[3] [decrease over given time]	SSP1-SUQ	20% until 2050	20% until 2050	20% until 2050	20% until 2050
	SSP2-BAU	None	None	None	None
	SSP3-DIV	None	None	None	None

1. The HE 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 HE classes termed HE-1 to HE-4. 2. When economies have sufficient investment potential (HE-2 and HE-3) or the societal paradigm strives for resource-efficient economies (SSP1) we assume power plants to be replaced after a service life of 40 years by plants with modern water-saving tower-cooled technologies. 3. Only in SSP1 (Sustainability Scenario), we assume by 2050 a 20% reduction in domestic water use intensity due to behavioral change.

Table B2. Per capita available surface water resources at country level [m3/capita/year].

		Sustainability			Middle of the Road			Regional Rivalry		
		2010	2030	2050	2010	2030	2050	2010	2030	2050
Advanced economies	Australia	34836	24357	21377	39642	27911	20292	39642	30746	25689
	Singapore	2096	1798	1739	2126	1788	1692	2126	1845	1839
	New Zealand	85738	71506	61989	84487	70068	64807	84487	74621	76761
	Republic of Korea	1963	2026	2118	2096	2011	2384	2096	2080	2675
	Brunei Darussalam	223281	190316	175639	221039	167955	145186	221039	171092	148640
	Japan	5255	5479	5902	5081	5544	5871	5081	5781	6677
East Asia	China	1742	1739	1992	1750	1740	1845	1750	1718	1783
	Mongolia	17150	13703	14005	17437	13813	12849	17437	13150	11347
Central and West Asia	Uzbekistan	3611	3249	3324	3758	3313	3187	3758	3094	2715
	Afghanistan	2703	1984	1447	2920	1933	1218	2920	1775	999
	Kyrgyzstan	5377	4776	5183	5654	4903	4934	5654	4537	4086
	Georgia	15091	16676	19253	15826	17135	19740	15826	15981	16466
	Turkmenistan	15791	14674	13992	16556	14571	13405	16556	13844	11859
	Armenia	2123	2046	2192	2242	2144	2343	2242	2019	2003
	Tajikistan	10353	9544	10290	10766	9565	9528	10766	8427	7053
	Kazakhstan	15717	13355	13620	15841	13509	12779	15841	13200	11940
	Azerbaijan	3802	3127	2953	3988	3160	3080	3988	3120	2956
Southeast Asia	LPDR	65967	53563	52894	62280	50580	44252	62280	47348	37777
	Viet Nam	10596	9466	9702	10064	8965	8463	10064	8694	7845
	Myanmar	25554	26306	29219	26047	24741	25830	26047	23614	23074
	Malaysia	22731	19082	17488	22813	17728	15595	22813	17102	14178
	Thailand	11078	10722	11418	10952	10265	10324	10952	10173	9998
	Philippines	7475	6550	5824	7057	5414	4932	7057	5096	4237
	Indonesia	16436	14840	14899	16346	14240	13749	16346	13855	12881
	Cambodia	39363	35448	35819	37786	32567	30269	37786	30408	25653
Pacific	Tonga	58347	59187	62570	69033	60437	62907	69033	51752	42621
	Papua New Guinea	188948	147762	124686	187879	128295	112302	187879	122614	100471
	Vanuatu	235020	179232	142344	250525	170875	122890	250525	162109	108321
	Samoa	79434	78356	82548	81663	74493	83491	81663	62677	54266
	Solomon Islands	316491	227706	175815	325554	192138	164073	325554	181035	142323
	Timor-Leste	10342	7773	6692	11529	7654	5214	11529	6459	3479
	Fiji	74885	71225	72766	81654	75406	69677	81654	71721	60370
South Asia	Pakistan	1166	900	841	1225	917	688	1225	857	580
	Maldives	13345	10362	10989	13769	11785	10221	13769	11420	9427
	Bangladesh	9761	8289	8702	10115	7877	7450	10115	7500	6581
	Bhutan	65826	49470	44359	69531	45562	36064	69531	45357	34764
	Nepal	7234	5377	5160	7375	5074	4180	7375	4690	3441
	India	2165	1844	1848	2233	1738	1531	2233	1656	1347
	Sri Lanka	3065	2892	3633	3251	2974	3126	3251	2873	2812

Table B3. Irrigation water demand [km^3/year].

		Sustainability			Middle of the Road			Regional Rivalry		
		2010	**2030**	**2050**	**2010**	**2030**	**2050**	**2010**	**2030**	**2050**
Advanced economies	Australia	27	28	28	27	28	28	27	28	28
	Singapore	0	0	0	0	0	0	0	0	0
	New Zealand	3	3	3	3	3	3	3	3	3
	Republic of Korea	12	11	12	11	11	11	11	11	11
	Brunei Darussalam	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Japan	35	35	36	35	35	35	35	35	35
	SUM	76	77	78	75	76	78	75	76	78
East Asia	China	642	656	684	635	635	658	635	635	658
	Mongolia	0.5	0.5	0.6	0.5	0.5	0.5	0.5	0.5	0.5
	SUM	643	657	684	635	636	659	635	636	659
Central and West Asia	Uzbekistan	55	56	57	54	56	56	54	56	56
	Afghanistan	51	51	53	50	51	52	50	51	52
	Kyrgyzstan	11	12	12	11	11	11	11	11	11
	Georgia	1	1	1	1	1	1	1	1	1
	Turkmenistan	22	22	23	21	22	22	21	22	22
	Armenia	2	2	2	2	2	2	2	2	2
	Tajikistan	9	9	9	9	9	9	9	9	9
	Kazakhstan	21	22	23	21	22	22	21	22	22
	Azerbaijan	11	11	12	11	11	11	11	11	11
	SUM	182	187	190	180	185	187	180	185	187
Southeast Asia	LPDR	3	3	3	3	3	3	3	3	3
	Viet Nam	45	45	45	45	45	45	45	45	45
	Myanmar	23	23	23	22	23	23	22	23	23
	Malaysia	3	3	3	3	3	3	3	3	3
	Thailand	56	56	57	56	57	57	56	57	57
	Philippines	16	15	16	16	17	16	16	17	16
	Indonesia	65	65	66	65	65	67	65	65	67
	Cambodia	4	4	4	4	4	4	4	4	4
	SUM	215	214	217	214	217	218	214	217	218
Pacific	Tonga	0	0	0	0	0	0	0	0	0
	Papua New Guinea	0	0	0	0	0	0	0	0	0
	Vanuatu	0	0	0	0	0	0	0	0	0
	Samoa	0	0	0	0	0	0	0	0	0
	Solomon Islands	0	0	0	0	0	0	0	0	0
	Timor-Leste	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Fiji	0.007	0.007	0.007	0	0	0	0	0	0
	SUM	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
South Asia	Pakistan	304	308	314	306	300	318	306	300	318
	Maldives	0	0	0	0	0	0	0	0	0
	Bangladesh	52	54	54	53	53	54	53	53	54
	Bhutan	0.6	0.7	0.6	0.6	0.6	0.7	0.6	0.6	0.7
	Nepal	9	9	9	9	9	9	9	9	9
	India	837	854	833	833	848	881	833	848	881
	Sri Lanka	10	10	10	10	9	10	10	9	10
	SUM	1213	1235	1220	1211	1221	1271	1211	1221	1271
	Asia SUM	2329	2369	2390	2315	2335	2413	2315	2335	2413

Table B4. Industrial water demand [km^3/year].

		Sustainability			Middle of the Road			Regional Rivalry		
		2010	**2030**	**2050**	**2010**	**2030**	**2050**	**2010**	**2030**	**2050**
Advanced economies	Australia	1.1	1.2	1.2	1.2	1.6	1.9	1.2	1.7	1.6
	Singapore	0.6	1.0	1.2	0.6	1.3	1.8	0.6	1.3	1.7
	New Zealand	0.5	0.5	0.5	0.5	0.6	0.5	0.5	0.7	0.7
	Republic of Korea	11	14	12	11	16	15	11	15	12
	Brunei Darussalam	0.2	0.1	0.0	0.2	0.2	0.3	0.2	0.3	0.3
	Japan	17	14	12	18	16	16	18	17	15
	SUM	30	30	27	32	36	35	32	36	32
East Asia	China	140	318	383	147	375	445	147	416	478
	Mongolia	0.3	0.6	0.7	0.4	0.8	1.1	0.3	1.0	1.4
	SUM	140	319	383	147	375	446	147	417	479
Central and West Asia	Uzbekistan	6	12	20	6	13	16	6	13	19
	Afghanistan	0.3	2.1	2.8	0.3	2.1	3.3	0.3	2.0	3.5
	Kyrgyzstan	0.5	0.8	1.3	0.5	1.0	1.3	0.5	1.1	1.6
	Georgia	1	3	4	1	4	5	1	3	5
	Turkmenistan	2.5	5.3	5.2	2.9	7.7	9.6	2.7	6.7	7.7
	Armenia	0.6	1.0	1.4	0.7	1.1	1.2	0.7	1.2	1.4
	Tajikistan	0.8	1.1	2.4	0.8	1.3	1.8	0.8	1.4	2.5
	Kazakhstan	7.0	9.9	9.8	8.4	15.1	16.0	8.1	13.9	14.3
	Azerbaijan	5.2	5.0	4.5	6.4	7.7	5.9	6.0	7.2	6.7
	SUM	24	40	52	28	52	60	27	50	62
Southeast Asia	LPDR	0.2	0.7	1.2	0.2	0.7	1.1	0.2	0.8	1.3
	Viet Nam	5	9	11	5	10	13	6	12	15
	Myanmar	0.5	0.4	0.6	0.6	0.5	0.6	0.6	0.6	0.7
	Malaysia	5	6	6	5	7	9	6	8	10
	Thailand	6	8	11	6	10	15	6	11	14
	Philippines	7	6	9	7	8	9	7	9	11
	Indonesia	16	15	18	17	19	25	17	22	26
	Cambodia	0.1	0.2	0.6	0.1	0.2	0.5	0.1	0.3	0.4
	SUM	40	45	57	41	56	73	42	63	79
Pacific	Tonga	0.002	0.001	0.000	0.002	0.002	0.003	0.002	0.003	0.003
	Papua New Guinea	0.2	0.1	0.2	0.2	0.2	0.3	0.2	0.3	0.3
	Vanuatu	0.002	0.001	0.000	0.002	0.002	0.002	0.002	0.003	0.003
	Samoa	0.002	0.002	0.000	0.002	0.004	0.004	0.002	0.004	0.004
	Solomon Islands	0.005	0.005	0.007	0.005	0.006	0.008	0.005	0.007	0.010
	Timor-Leste	0.01	0.02	0.11	0.01	0.02	0.03	0.01	0.02	0.06
	Fiji	0.02	0.02	0.02	0.02	0.03	0.04	0.02	0.03	0.04
	SUM	0.2	0.2	0.3	0.2	0.3	0.4	0.2	0.3	0.5
South Asia	Pakistan	4	5	6	4	8	6	5	10	12
	Maldives	0	0	0	0	0	0	0	0	0
	Bangladesh	1.8	2.9	6.8	1.8	4.3	7.9	1.9	4.8	6.6
	Bhutan	0.0	0.1	0.2	0.0	0.1	0.2	0.0	0.1	0.2
	Nepal	0.0	0.3	1.0	0.1	0.3	0.7	0.1	0.3	0.5
	India	36	69	116	38	77	103	38	86	105
	Sri Lanka	0.6	1.5	2.4	0.7	2.1	3.4	0.7	2.2	2.9
	SUM	43	79	132	45	91	121	45	103	128
Asia SUM		278	512	652	293	612	736	293	669	780

Table B5. Municipal water demand [km^3/year].

		Sustainability			Middle of the Road			Regional Rivalry		
		2010	**2030**	**2050**	**2010**	**2030**	**2050**	**2010**	**2030**	**2050**
Advanced economies	Australia	4	6	7	5	6	7	4	7	8
	Singapore	0.2	0.3	0.5	0.2	0.4	0.5	0.2	0.4	0.7
	New Zealand	0.8	1.1	1.2	0.9	1.1	1.3	0.9	1.2	1.4
	Republic of Korea	6.7	7.2	7.0	6.9	8.2	8.2	6.9	8.3	9.0
	Brunei Darussalam	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Japan	15	13	12	15	14	13	15	14	14
	SUM	27	27	28	28	30	30	28	31	33
East Asia	China	64	168	204	68	198	232	66	192	261
	Mongolia	0.1	0.4	0.7	0.1	0.4	0.8	0.1	0.4	0.9
	SUM	64	168	205	68	198	233	67	192	262
Central and West Asia	Uzbekistan	4	6	10	4	7	10	4	7	13
	Afghanistan	0.4	1.3	4.2	0.5	1.4	3.7	0.5	1.4	3.9
	Kyrgyzstan	0.5	0.7	1.2	0.5	0.9	1.3	0.5	0.9	1.6
	Georgia	0.8	1.6	2.3	0.8	1.8	2.4	0.8	1.8	2.7
	Turkmenistan	0.8	1.7	2.1	0.9	2.7	4.1	0.8	2.5	3.7
	Armenia	1.1	1.7	2.5	1.2	2.0	2.5	1.1	2.0	2.8
	Tajikistan	0.5	0.9	1.8	0.5	1.1	1.6	0.5	1.1	2.1
	Kazakhstan	1.1	1.8	1.9	1.1	2.3	2.8	1.1	2.2	2.7
	Azerbaijan	1.6	2.2	2.4	1.9	2.9	2.5	1.8	2.7	3.0
	SUM	10	18	28	11	22	31	11	22	36
Southeast Asia	LPDR	0.2	0.6	1.2	0.2	0.7	1.2	0.2	0.7	1.6
	Viet Nam	6	8	11	6	10	12	6	10	15
	Myanmar	1.6	1.9	2.2	1.7	2.2	2.4	1.7	2.3	2.8
	Malaysia	2.7	3.4	3.9	2.8	4.1	5.0	2.8	4.4	6.2
	Thailand	2.6	4.6	5.0	2.6	5.2	5.7	2.6	5.5	6.8
	Philippines	6	10	16	6	11	18	6	11	21
	Indonesia	10	23	23	10	27	29	10	28	34
	Cambodia	0.1	0.3	0.6	0.1	0.3	0.8	0.1	0.3	0.6
	SUM	28	52	63	29	60	74	29	62	88
Pacific	Tonga	0	0	0	0	0	0	0	0	0
	Papua New Guinea	0.1	0.3	0.6	0.1	0.3	0.5	0.1	0.3	0.6
	Vanuatu	0	0	0	0	0	0	0	0	0
	Samoa	0	0	0	0	0	0	0	0	0
	Solomon Islands	0.000	0.001	0.006	0.000	0.002	0.004	0.000	0.002	0.006
	Timor-Leste	0.001	0.004	0.002	0.001	0.005	0.004	0.001	0.005	0.005
	Fiji	0.02	0.02	0.04	0.02	0.02	0.04	0.02	0.03	0.04
	SUM	0.2	0.3	0.6	0.2	0.3	0.5	0.2	0.3	0.6
South Asia	Pakistan	6	10	15	6	10	17	6	11	20
	Maldives	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Bangladesh	3	7	11	3	7	12	3	7	14
	Bhutan	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.1	0.1
	Nepal	0.3	0.7	1.9	0.3	0.7	1.8	0.3	0.8	1.5
	India	41	94	143	42	105	133	42	111	185
	Sri Lanka	0.5	1.3	1.3	0.5	1.5	1.6	0.5	1.6	1.9
	SUM	50	113	173	52	125	166	51	131	221
	Asia SUM	180	378	497	189	435	534	186	438	641

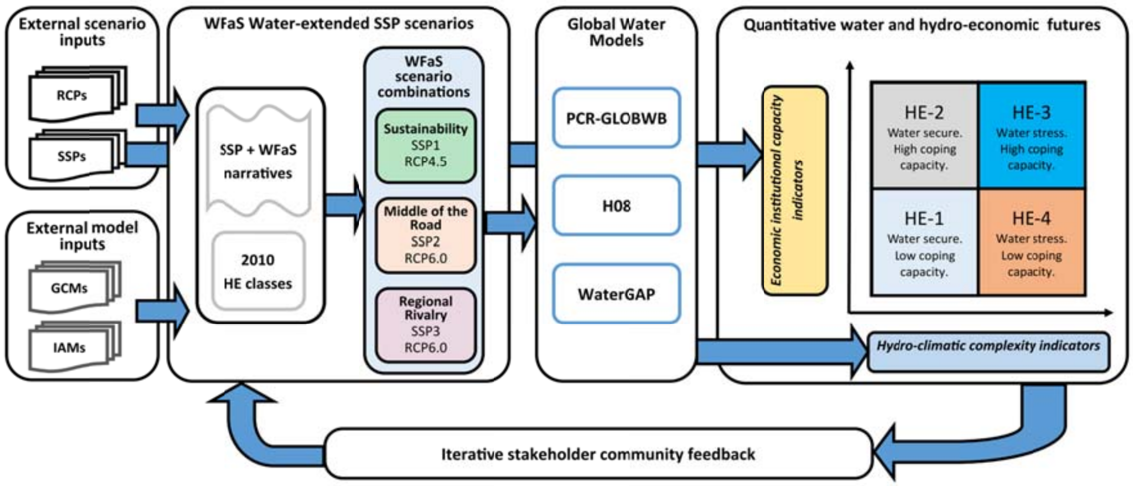


Figure 1. Methodological framework of the Water Future and Solutions initiative fast track. (RCPs: Representative Concentration Pathways, SSPs: Shared Socioeconomic Pathways, GCMs: Global Climate Models, IAMs: Integrated Assessment Models, WFaS: Water Future and Solutions, HE: Hydro-economic classification).

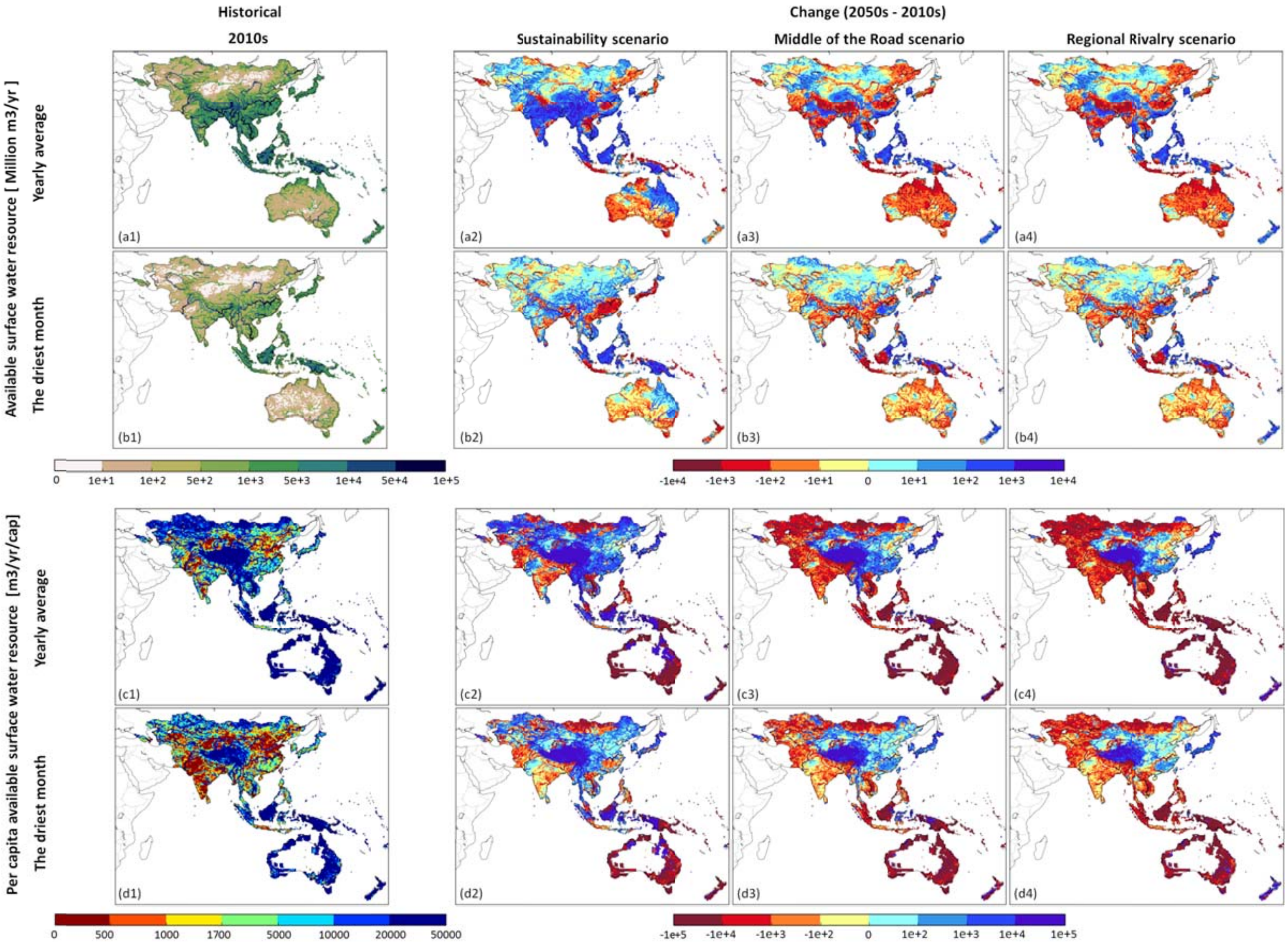


Figure 2. (a) Yearly average available surface water resources [Million m^3/yr] (b) Available surface water resources in the driest month [Million m^3/yr], (c) Yearly average available surface water resources per capita [m^3/yr/cap], (d) Available surface water resources per capita in the driest month [m^3/yr/cap].

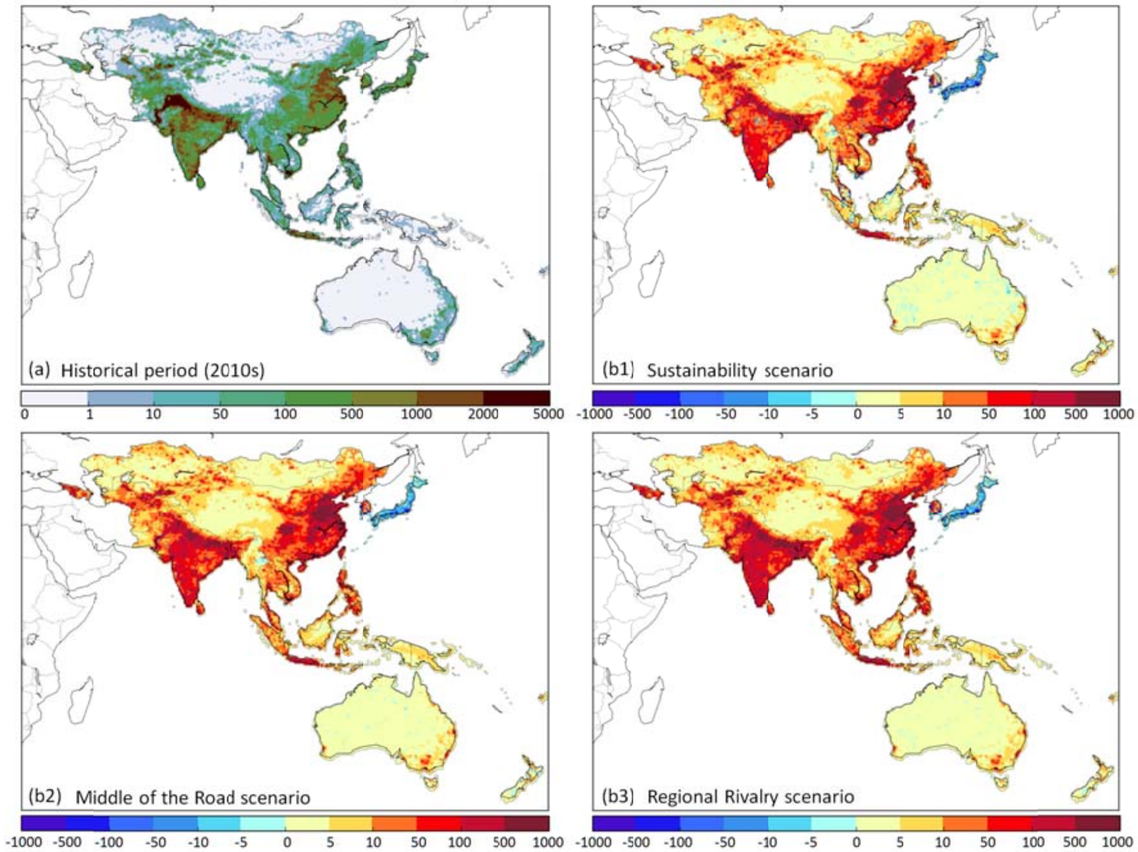


Figure 3. Water demand in the 2010s and change between the 2010s and the 2050s for each scenario [Million m3/yr]. Water demand is the total of irrigation, industrial and municipal water demand.

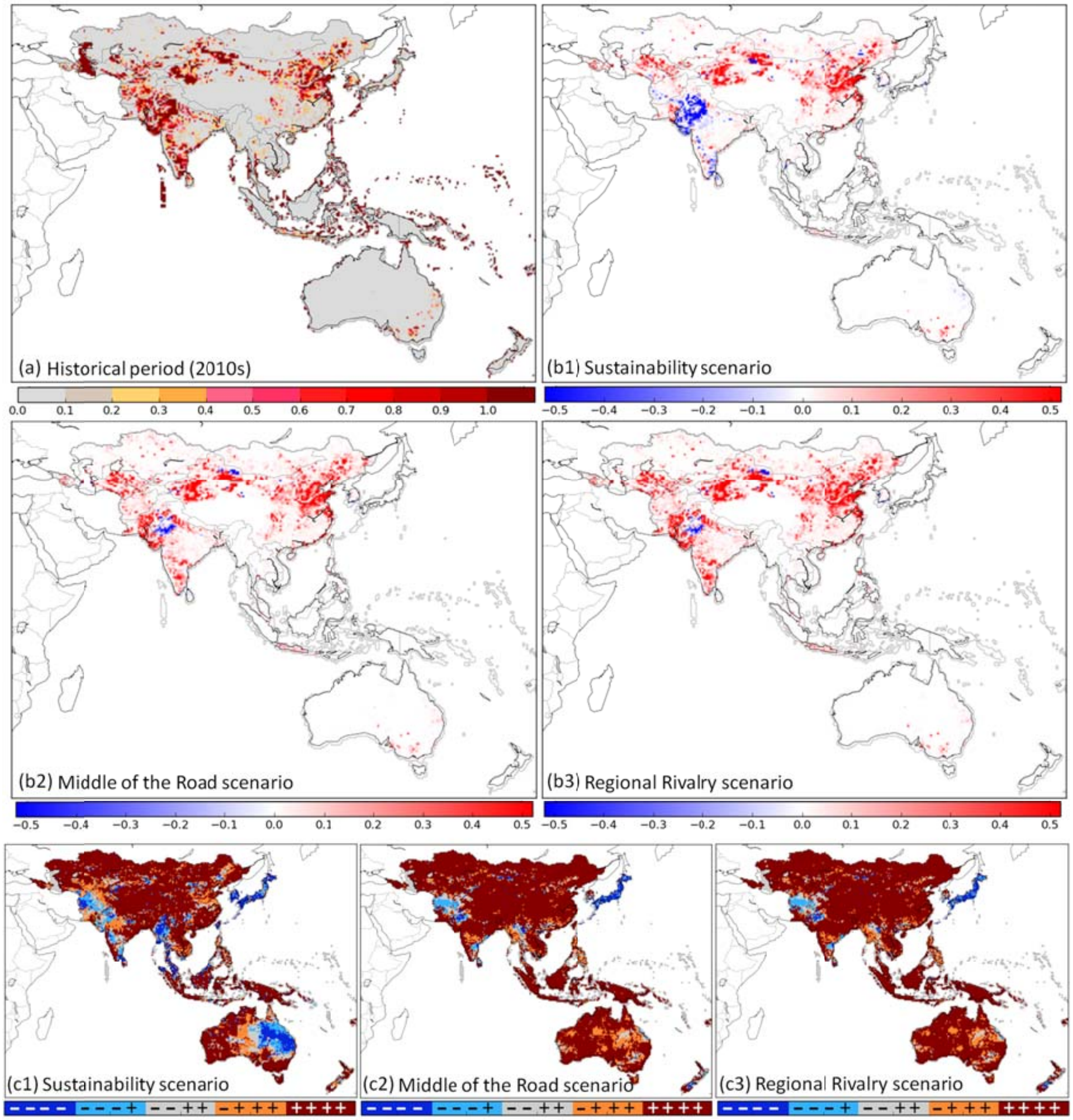


Figure 4. Withdrawal to availability ratio (WTA): (a) historical value in the 2010s; (b) changes in the WTA in the 2050s compared with the 2010s for each scenario; (c) decadal consistency of trend during the 2010s to the 2050s. In Figure 4c, blue and red are consistent increase and decrease throughout the period, respectively. Orange indicates decrease in three decades and increase in a decade. Light blue is opposite.

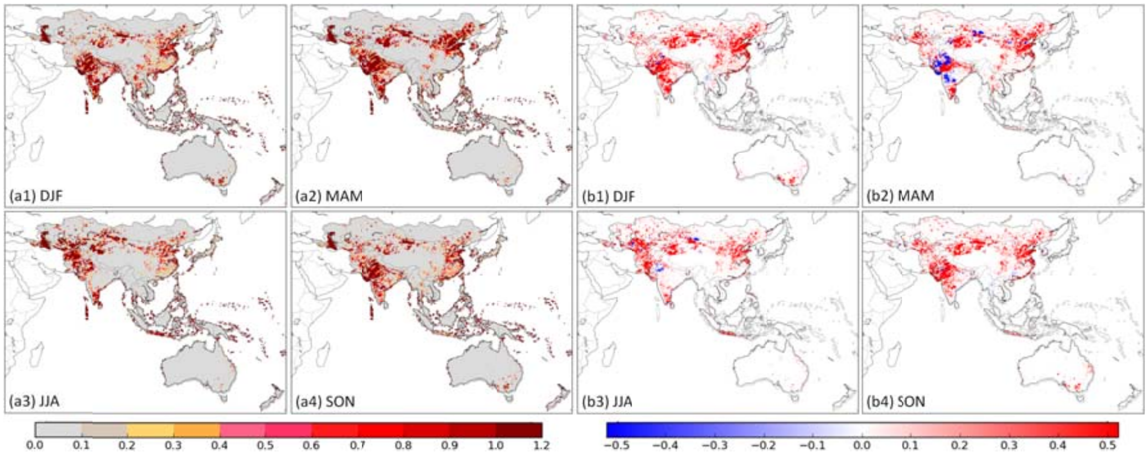


Figure 5. (a) The seasonal water scarcity index in the 2010s. (b) Change in the seasonal water scarcity index between the 2010s and the 2050s in the Middle of the Road scenario. (DJF: December-January-February, MAM: March-April-May, JJA: June-July-August, and SON: September-October-November).

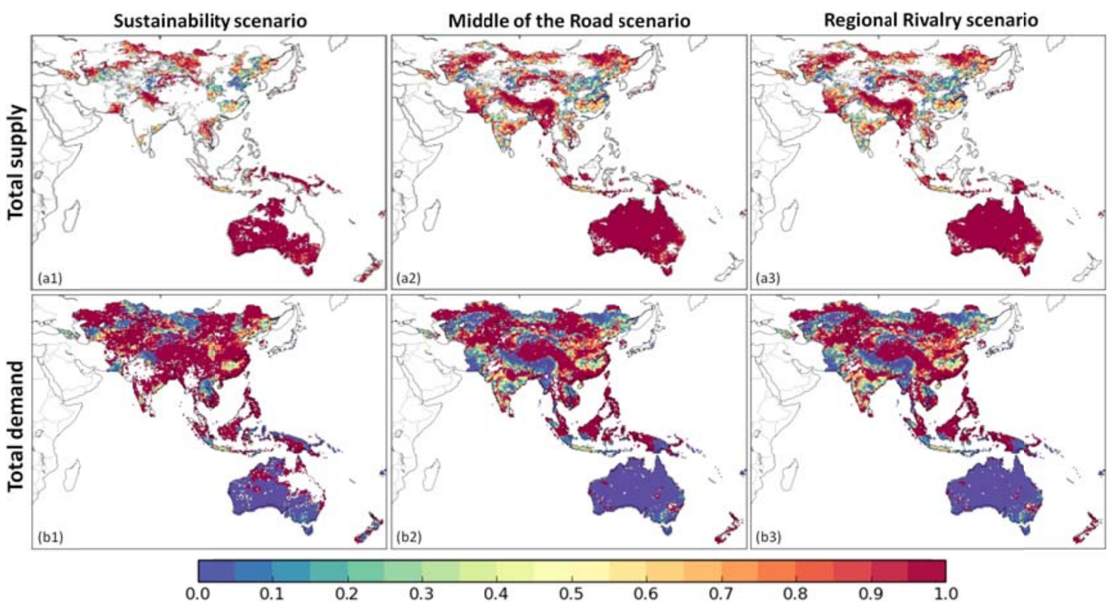
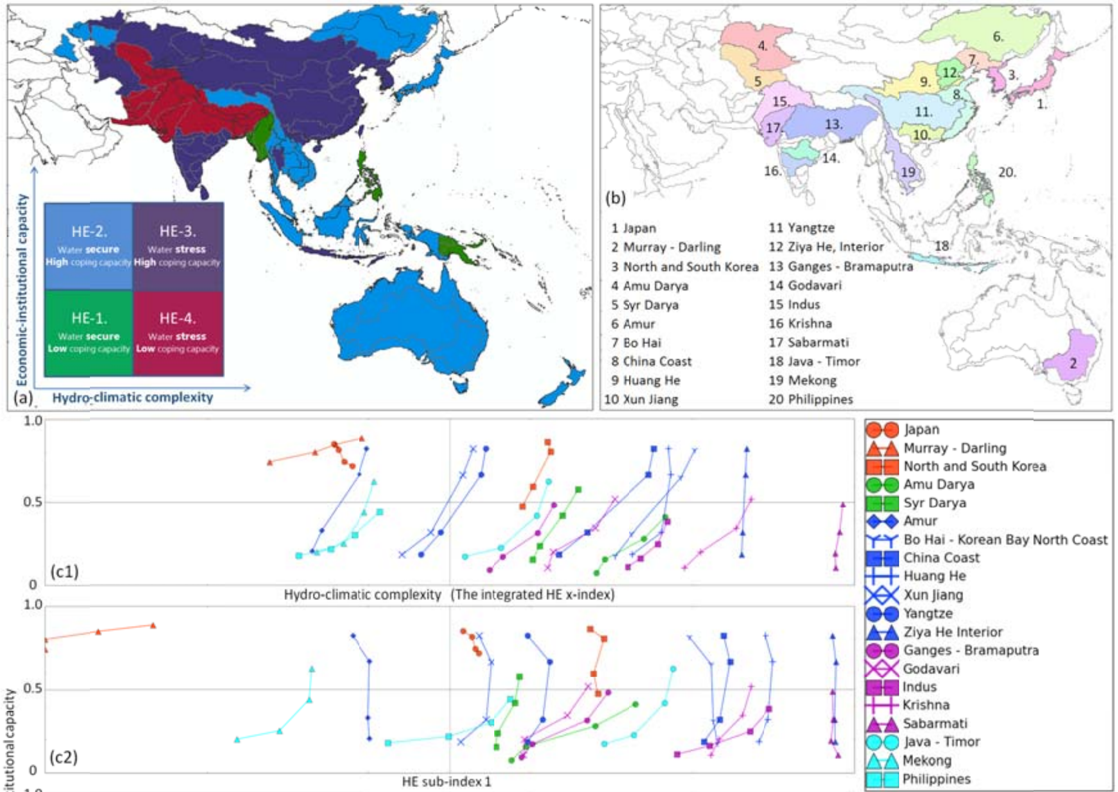


Figure 6. Attribution ratio to increases in the WTA score for: (a) Supply side, and (b) Demand side. A value of attribution rate of a factor equals to 0 indicates no impact of that factor on water scarcity, while a value of 1 indicates that water scarcity is totally driven by that factor.



Basin	Area [$10^3 km^2$]	Population 2010 [Million]	Population 2050 [Million]
Japan	369	125	113
Murray - Darling	930	2	3
North and South Korea	176	66	66
Amu Darya	798	27	44
Syr Darya	1113	27	33
Amur	2076	68	64
Bo Hai	351	63	61
China Coast	642	371	365
Huang He	832	131	126
Xun Jiang	414	92	88
Yangtze	1792	396	360
Ziya He, Interior	340	135	134
Ganges - Bramaputra	1673	701	995
Godavari	315	76	109
Indus	868	195	314
Krishna	276	91	132
Sabarmati	524	105	158
Java - Timor	218	157	192
Mekong	807	69	77
Philippines	295	99	154

Figure 7. Results of basin scale hydro-economic analysis in the Middle of the Road scenario. (a) Hydro-economic class in the 2050s. (b) Map of selected 20 Asian major basins. (c) Changes in the hydro-economic classification of basins over time. (c1) the integrated HE index; (c2) sub-index 1 of per capita available surface water resources; (c3) sub-index 2 of water use intensity; (c4) sub-index 3 of monthly variability of runoff (seasonality). Index 4 of external dependency is not included because this index is zero in a basin-scale analysis. Colors indicate different Asian sub-regions.

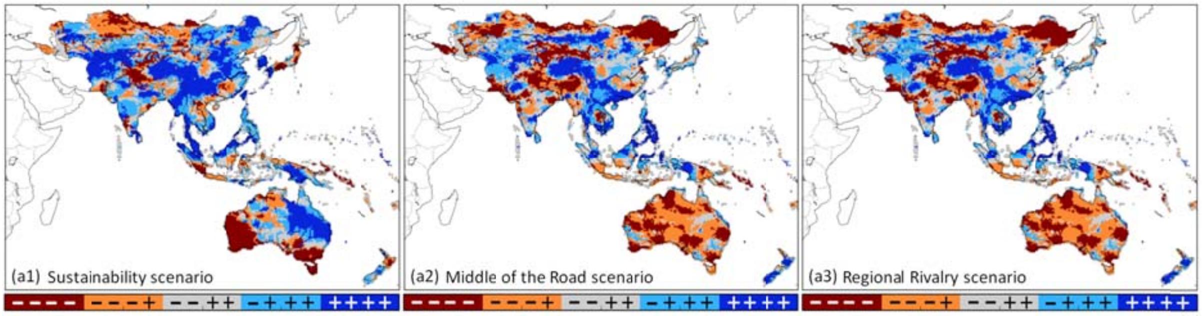


Figure B1. Decadal consistence of change in available surface water resources during the 2020s-2050s compared to 2010s. Blue and red are consistent increase and decrease throughout the period, respectively. Orange indicates decrease in three decades and increase in one decade. Light blue is opposite.

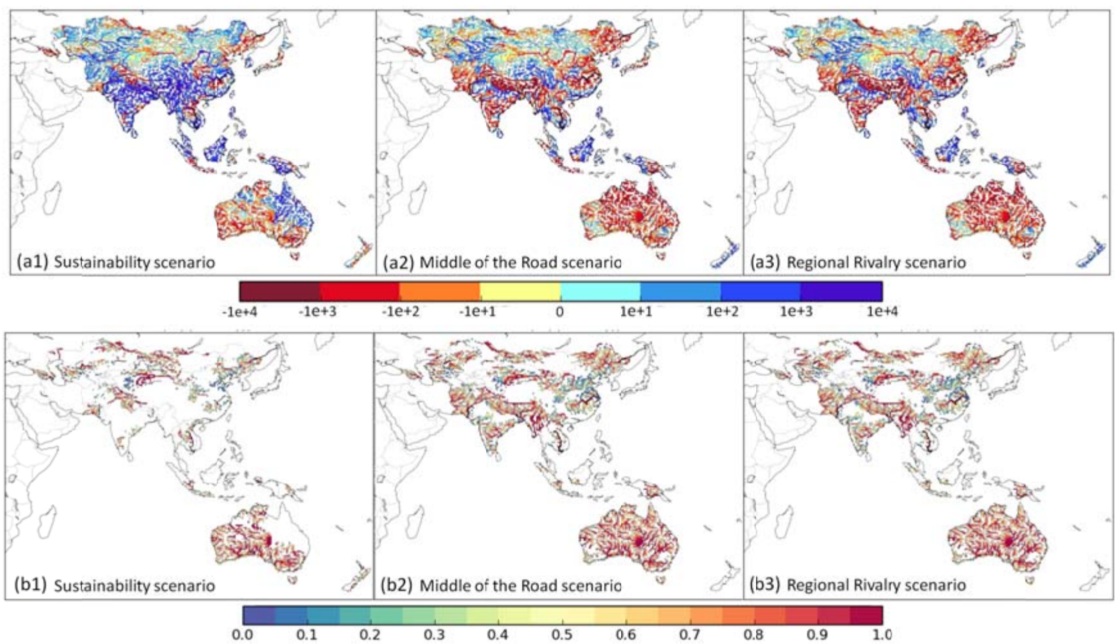


Figure B2. (a) Change in inflow for each grid between the 2010s and 2050s [Million m3/yr], and (b) attribution ratio of inflow to increases of the WTA score in the 2050s.

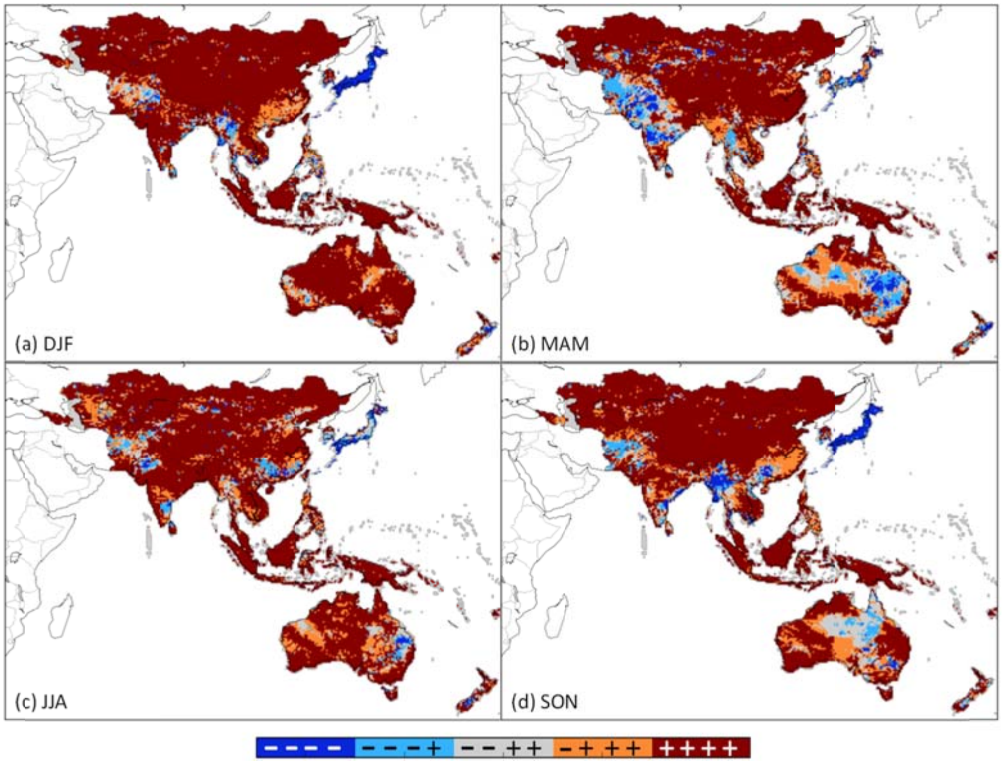


Figure B3. Consistency of change in water scarcity for each season during the 2020s to the 2050s compared with the 2010s under the Middle of the Road scenario. The number of "+" and "-" in the color bar indicates the number of decade with increase and decrease in score of withdrawal to availability ratio (WTA). For instance, dark red shows a consistent increase in the score through four decades, and orange indicates that only one decade gives a lower score but rest of decades face higher score of WTA.

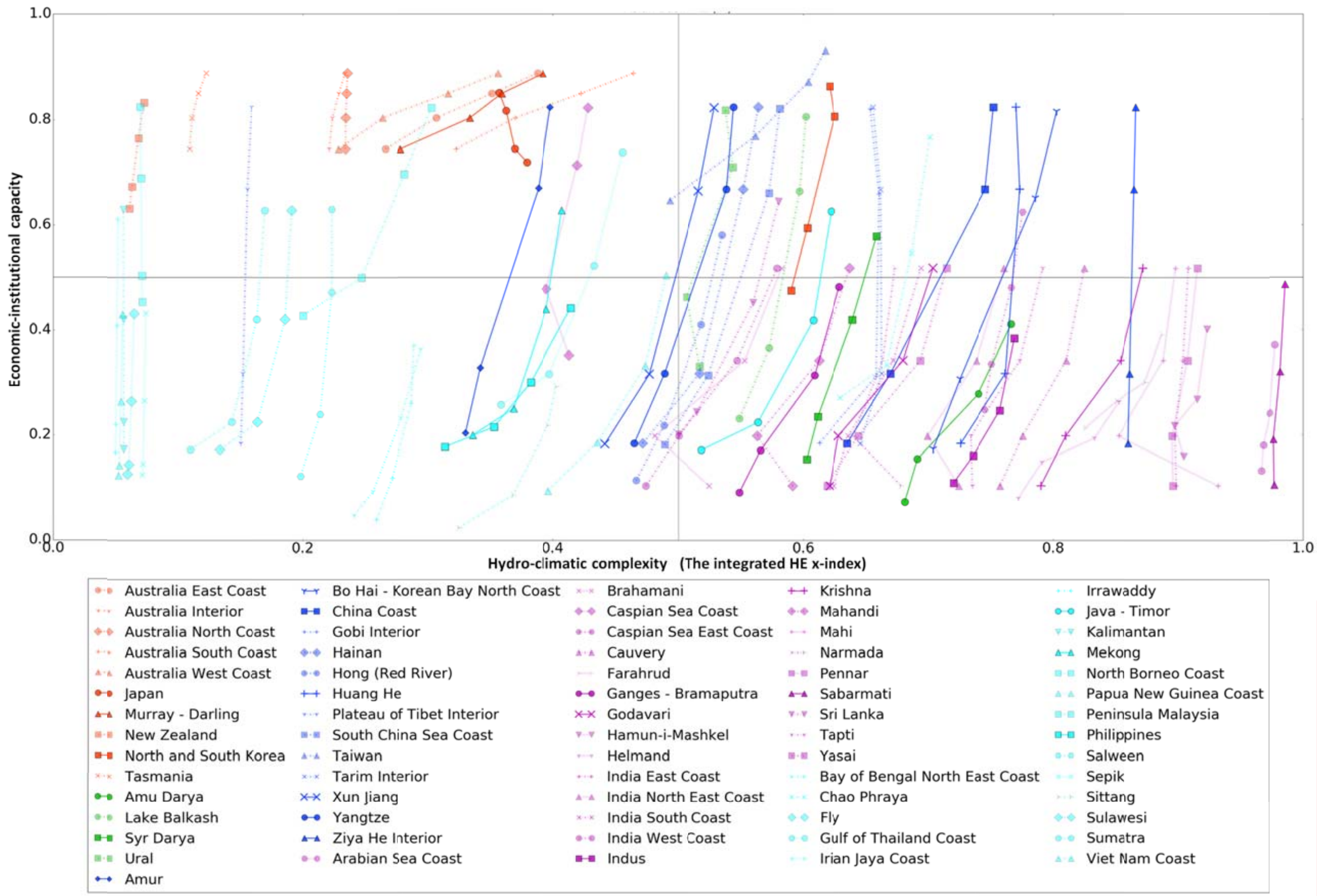


Figure B4. Shifts of Asian basins in the HE dimension in the Middle of the Road scenario. The x- and y-axes indicate the integrated HE index of the hydro-climatic complexity and the economic-institutional capacity, respectively. This figure is similar to Figure 7c1 but for all 40 basins. Because GDP per capita will grow in all basins, all basins shift upward in the HE dimension. Each marker in a plot is about year 2000, 2010, 2030 and 2050. Colors indicate different Asian sub-regions.