South Asia suffers severe water scarcity even under the Paris Agreement

Mehnaz Rashid

National Taiwan University <https://orcid.org/0000-0002-0602-5298>

Ren-Jie Wu

National Taiwan University

Yoshihide Wada

The International Institute for Applied Systems Analysis <https://orcid.org/0000-0003-4770-2539>

Hannes Müller Schmied

Goethe University Frankfurt <https://orcid.org/0000-0001-5330-9923>

Min-Hui Lo (✉ minhuilo@ntu.edu.tw)

Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan

<https://orcid.org/0000-0002-8653-143X>

Article

Keywords:

Posted Date: February 11th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1293828/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

South Asia suffers severe water scarcity even under the Paris Agreement

Mehnaz Rashid^{*1}, Ren-Jie Wu¹, Yoshihide Wada², Hannes Müller Schmied³, Min-Hui Lo^{*1}

¹Mehnaz Rashid (geo.mehnaz@gmail.com)

¹Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan

¹Ren-Jie Wu (wurjicnip@gmail.com)

¹Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan

²Yoshihide Wada (wada@iiasa.ac.at)

²International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

^{3,4}Hannes Müller Schmied (Hannes.Mueller.Schmied@em.uni-frankfurt.de)

³Institute of Physical Geography, Goethe University Frankfurt, Frankfurt, Germany

⁴Senckenberg Leibniz Biodiversity and Climate Research Centre (SBiK-F), Frankfurt, Germany

¹Min-Hui Lo (minhuilo@ntu.edu.tw)

¹Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan

Letter:

Water scarcity (WS) is projected to increase as a result of future climate and population changes, and its impacts will be hazardous to vulnerable groups of people in South Asia (SA). We present the first assessment of WS in SA under the Paris Agreement, using two global hydrological models (GHM) forced by three global climate models (GCM) under the RCP 6.0. Results show that a significant alteration in the hydrological fluxes contributes to the decline in water availability, along with an intense increase in water consumption that augments WS. The seasonal shifting in WS significantly increases the population affected by approximately 16% in June to September (JJAS) to 42% in December to February (DJF) under 1.5 °C warming. We also highlight spatial hotspots of WS in SA, including North-central, Northwestern, and Southern India, Eastern Pakistan, Northern, and Northwestern Bangladesh. We observe a 1.5 °C temperature increase as a critical point for WS in SA with a profound impact on 875 million people and suggest the Paris Agreement temperature target of even 1.5 °C will not ubiquitously alleviate future warming-driven WS. Hence, immediate mitigations and legislations are required to curtail WS in SA.

Climate change and its effects represent an immediate threat to human society and the environment¹. Considering the substantial dangers associated with increasing temperatures, the Paris Agreement 2015 enshrined a two-tier global temperature control goal: limiting global warming to 1.5 °C and holding the increase below 2 °C above pre-industrial levels recognizing that this would significantly reduce the risks and impacts of climate change². Water scarcity has emerged as one of the major threats to societal wellbeing due to its direct impact on food and water security, socioeconomics, and hydroclimate^{3–5}. Since the last century, an increase in anthropogenic warming and water consumption has aggravated WS in many parts of the world^{6–10}. Similarly, future projections suggest a substantial increase in WS as a result of climate change and population increase^{4,5,11–16}, particularly in vulnerable regions like South and East Asia, the Middle East, Central, and Western North America, parts of Australia, and Northern Africa^{5,6,9,13,15–19}. The number of people affected, however, depends greatly on the assessment method, time frame, and the reference period used^{5–7,16}. Thus, using annual WS assessments could mask the number of people affected, over-shadowing particular seasons of the year in which WS occurs^{5,6}. Particularly, water availability changes seasonally in sub-tropical and tropical regions due to monsoonal rainfall and river discharge changes^{15,20,21}. Therefore, WS and the changes in the hydrological components should be evaluated on a seasonal scale.

There are two primary contributors to WS: 1) decline in water availability and 2) increase in water consumption. Anthropogenic warming results in declines in the availability of freshwater resources in many regions by altering the terrestrial hydrological cycle (precipitation, ET, and discharge)^{20,22–25}. On the other hand, increasing population and changing socioeconomics lead to increases in per capita freshwater consumption^{18,26–29}. However, the impact of climate change largely depends on the vulnerability of the people and their resilience. For example, people living in densely populated and/or lower and medium income regions are at greater risk of weather and climate hazards^{1,18,24}.

With a population of 1.8 billion people³⁰, South Asia (SA) has been identified as one of the most susceptible regions for climate (such as water stress, floods, drought, and heat stress) and socioeconomic vulnerability^{15,31–34}. Saeed et al. (2021)³¹ reported an extreme severity in the heat stress across SA at 1.5 °C global warming, making this low warming goal undesirable for the South

Asian Region. In the middle of the road Shared Socioeconomic Pathways, or SSP2 projections, the South Asian population is expected to reach around 2 billion around 1.5 °C global temperature increases above pre-industrial level, exerting further pressure on the water resources and food security. For instance, India, the largest country in the region with a current population of 1.3 billion, is already facing acute water shortage^{8,32,35}, with about 600 million people presently living under extreme WS³⁴. Water availability in India, Pakistan, and Bangladesh is projected to decline considerably by 2030^{34,36,37}. Severe water demand has resulted in significant groundwater exploitation in the region, leading to overexploitation of the prominent aquifers^{38,39}. The concurrent impacts of rising temperatures, CO₂ concentrations⁴⁰, and population⁴¹ have resulted in a decline in freshwater resources and caused an extreme WS.

Several studies have analyzed contemporary and future WS assessments globally and regionally^{5,15,16,26,28,33,42–44}. However, only a few studies focus on the seasonal WS assessment in SA; for example, Satoh et al. (2017)¹⁵ reported a substantial seasonal variation in WS in 2050 compared to 2010. Overall, the seasonal variations in the WS and the hydrological fluxes in SA in the context of the Paris Agreement (1.5 and 2 °C of temperature increase compared to the pre-industrial period) are poorly known. The preeminent reason is the dearth of required data for these warming scenarios⁴⁵. It is thus indispensable to understand how WS will manifest in this largely populated region under Paris temperature targets. Therefore, this study aims to assess the changes in the seasonal and spatial patterns of WS and hydrological fluxes. We explore the number of people affected by various degrees of WS in the 1.5 and 2 °C warming scenarios under SSP2 population and RCP 6.0 climate projections using Inter-Sectoral Model Intercomparison Project Phase 2b (ISIMIP2b⁴⁶) model simulations. Total water availability and water consumption are calculated seasonally, taking a 31-year mean from an ensemble GHM-GCM simulations. According to the climatological cycle in SA, we separate the year into 4 different periods, which are from June to September (JJAS), October to November (ON), December to February (DJF), and March to May (MAM). Total water availability is estimated as the sum of discharge and water consumption in each grid, and water consumption is the sum of water use from each sector. Furthermore, we evaluate the control of hydrological variables (i.e., precipitation and ET) on WS using linear regression analysis. A comprehensive description of scenario analysis, including how WS is defined and calculated is given in the Methods section.

Results

Results from the ensemble of two hydrological and three climate models show that WS in SA will increase significantly in a 1.5 °C warming scenario with a robust spatiotemporal variability (Fig. 1a), and the absolute changes compared to the pre-industrial period are considerable (Fig. 1b). Spatial WS hotspots in the region are located in North-central, Northwestern and Southern India, Eastern Pakistan, Northern, and Northwestern Bangladesh; given the socio-economic situation, these areas can be most vulnerable to water crises in the future. On the other hand, the Himalayan region (Nepal, Bhutan, North and Northeastern India, and Northern Pakistan), Central-eastern India, Western Pakistan, and most of Sri Lanka are relatively unaffected. A robust seasonality in WS is observed, which is lowest in JJAS and peaks in DJF and MAM (Fig.1). To explore how strongly seasonality affects water security in the future, Table 1 shows the exposure of the human population to WS in each season. For example, in JJAS, 157 million (7.6% of the total population in SA) people are projected to face severe WS, and the number increases to 341 million (16.5%), 610 million (29.4%), and 558 million (28.4%) in ON, DJF, and MAM, respectively. Of the numbers mentioned above, India alone is projected to have 494 million (31.3% of the total population in India) and 503 million (31.8%) people under severe WS in DJF and MAM, respectively (Table 1 and Supplementary Table 1).

We observe a considerable increase in the number of people living under severe WS in a 1.5 °C warmer world compared to the pre-industrial period. For example, population living under severe WS will increase from 1.5% to 7.6 %, 3.7% to 16.5%, 5% to 29.4%, and 6% to 28.4% (% of total population) in JJAS, ON, DJF, and MAM, respectively (Table 1 and Supplementary Table 1). The South Asian population for the pre-industrial reference period (1660-1860) is 286 million, and it is expected to increase 7-fold around the 1.5 °C warming period under SSP2 population projections and reach 2 billion.

Please note that the individual GCMs cross the 1.5 °C temperature thresholds in different periods compared to the pre-industrial reference period. Thus, we calculate the population affected by the different WS grades corresponding to the central 31-year temperature threshold for individual GCMs and subsequently use the ensemble population values for our analysis (see Methods).

Altogether, about 42% of the South Asian population will suffer from moderate to severe WS for half of the year (Table 1). This will result in water crises in this already vulnerable region with severe over-exploitation of freshwater resources. WS in both 1.5 and 2 °C warming scenarios is analogous compared to the pre-industrial period and additional warming of 0.5 °C does not reveal a significant change in WS pattern (Fig. 1b, Supplementary Fig. 1b). This is primarily due to stable levels of discharge (Supplementary Figs. 2b and 3b) along with the counterbalance of increased precipitation (Supplementary Figs. 2a and 3a) by the increase in ET (Supplementary Figs. 2c and 3c). A slight increase in the total number of people affected is observed mainly due to the increase in the total population (Supplementary Table 2).

Two major factors affecting the WS in a warmer world are water availability and water consumption (Fig. 2). Water availability shows enormous heterogeneity in its seasonal and spatial patterns, and the absolute changes compared to the pre-industrial period are extensive (Fig. 2a). JJAS is the most plentiful water season, with the average availability going up to 1200 mm in some of the prominent river basins (Supplementary Fig. 4a), signifying the importance of both summer monsoon (which supplies approximately 80% of the rainfall to the region)⁴⁷ and river discharge that is maximum during the summer season²¹. However, compared to the pre-industrial period, water availability in JJAS declines in the Himalayan region, North-central, Northwestern and Southern India, Eastern Pakistan, and Bangladesh. This region abodes important rivers like the Indus, Ganges, and Brahmaputra in the north, and Krishna and Cauvery in the south. The decrease of water availability in these areas is likely due to decreases in the discharge and/or precipitation (Supplementary Figs. 3a and 3b). Fig. 2 further indicates that during ON, declines are observed in North-central India, Eastern Himalayas, and Western Bangladesh. A slightly increasing trend is observed in the rest of SA (e.g., Western Himalayas, Sri Lanka, and most parts of South and Central India). During DJF, the Western Himalayan region shows a slight increase in availability, while the Eastern Himalayan region and Northeastern Pakistan show a modest decrease. During MAM, the Himalayan region and Eastern Bangladesh show an increasing trend, and North-central India and East Pakistan show a slight increase in water availability.

Likewise, consumption projections show significant increases over most of SA compared to the pre-industrial period (Fig. 2b). The spatial pattern during JJAS and ON reveals the increased

consumption over North-central and Northwestern India, the most populated regions, along with Eastern Pakistan and Bangladesh (Supplementary Fig. 4b). Western Himalayan region (mainly the Thar desert region), East-central India, and West Pakistan show negligible water consumption changes in DJF and MAM due to reductions in water availability. Further, water consumption is strongly amplified by the increase in ET, mostly linked to extensive agricultural activities and the increase in mean temperature⁴⁸⁻⁵⁰. The spatial pattern of water consumption (Fig. 2a) largely follows the spatial pattern of the population (Supplementary Fig. 8a) and ET (Supplementary Fig. 2c).

The ensemble precipitation projections for JJAS show significant increases (Supplementary Fig. 2a) over Central India and Bangladesh, and slight increases over the Western Himalayas, Southeastern India, and Sri Lanka. However, a significant decline in rainfall is seen in Southwestern coastal and North-central India, and the Middle and Eastern Himalayan region. In SA, JJAS is the main rainfall season, with approximately 80% of the rainfall occurring during this season⁴⁷. During ON, Sri Lanka, the coastal regions of India, Southeastern, and Southwestern India show a considerable increase in precipitation. In addition, the river discharge during JJAS decreases in the Himalayan region, North-central India, Eastern Pakistan, and Southern India, areas that include some prominent river basins (the Indus, Ganga-Brahmaputra, and Lower Krishna basins). An increase in discharge is observed in Central India, while the rest of SA shows a minor change. In other seasons, the river discharge generally shows a declining trend in the Himalayas and North-central India with few exceptions. For example, the Western Himalayan region slightly increases during ON, DJF, and MAM, while the Eastern Himalayan region shows increased discharge during MAM.

ET shows considerable increases during all the seasons, except for the Himalayan region, Western India (mainly Thar dessert), and Southwestern Pakistan (Supplementary Fig. 3c). ET is high during the dry seasons, particularly in the North-central, Northwestern India, Eastern Pakistan, and Bangladesh, areas that have the highest population and the most irrigation activities. Global warming^{48,49} and irrigation activities^{50,51} are the two drivers that lead to a massive increase in ET in a warmer world. The changes in the hydrological fluxes strongly control WS variability. To scrutinize the individual contribution on seasonal and spatial WS, we perform a statistical

regression analysis with precipitation and ET as explanatory variables, given the availability is a direct outcome of discharge and consumption (see Methods). Results reveal a robust spatiotemporal control of precipitation and ET on WS (Fig. 3). Largely, WS is dominated by changes in precipitation in JJAS over most regions, while ET plays a significant role in DJF for most of the regions. In MAM and ON, the changes in precipitation are dominant over the Himalayan region, North-eastern India, Bangladesh, and southern India. The changes in the ET are dominant over Pakistan, western, and Central India.

The aforementioned results are for the 1.5 °C warming scenario and a similar pattern of change is observed in a 2 °C warming scenario (Supplementary Information).

Discussion

This study provides the first seasonal WS assessment in SA under the Paris Agreement temperature targets and identifies the responsible hydrological components for the driving force of declining water availability. For example, precipitation and ET show an increasing trend in most regions. The large rise in precipitation and ET can be a result of an increase in mean temperature^{48,49} and increased agricultural activities in the region^{50,51}. The river discharge projections show a steady decline in most regions during the monsoon and post-monsoon seasons. Previous studies have reported increases in discharge in SA for similar warming scenarios but under different concentration pathways, in which the warming targets occur early^{5,19,20}. Nevertheless, most of these studies did not consider seasonal variations, which could be the reason for the difference. Furthermore, in the northern river basins, the decline could be linked to the reduced glacier meltdown, e.g., 80% of Indus basin river flow has been attributed to glacier melt down⁵² that is projected to peak around the year 2030 for middle and low emission scenarios⁵³. Despite increases in the precipitation, the counter impact of the increases in ET and decreases in the discharge is more dominant, resulting in overall negative effects on water availability. Our study finds a large increase in water consumption with a strong spatiotemporal variability mostly in the highly populated regions of North-central India, Eastern Pakistan, and Bangladesh, even when the human impact is set at the year 2005. The increased WS (Fig. 1) in SA is a result of the combined impact of decreased water availability and increased consumption. The consumption factor plays a crucial

role in the densely populated regions, while changes in water availability are more widely distributed with substantial spatiotemporal variability and a plausible broader impact on WS.

Projected changes in seasonal WS, in the 1.5 °C warming scenario, will have a severe societal impact with a sizeable reshuffling in the number of people affected in the region. These changes represent a significant increase compared to the pre-industrial period. For example, DJF and MAM are projected to be the most affected seasons in terms of WS, corresponding to the winter cropping season locally referred to as Rabi, thus, jeopardizing the water and food security of millions of people living in the region. Our findings are in agreement with previous studies that report severe WS in SA^{6,8,15,16,34,37,43}. However, we observe some disagreements with the studies using RCP 8.5 warming scenarios that report an increase in water availability in SA^{5,19,20}. None of these studies analyzed seasonal changes in water availability, one of the critical dimensions of WS in this monsoonal region. The results suggest that changes in the ET act parallel with the changes in precipitation to augment WS. The seasonal and spatial control of these hydrological fluxes shows extreme variability with precipitation as a dominant factor in JJAS and ET as a dominant factor in DJF for most regions. Precipitation in MAM and ON controls WS over the Himalayan region, North-eastern India, Bangladesh, and southern India, while ET controls WS over Pakistan, western, and Central India. Thus, this study provides a better understanding of the underlying factors that augment WS both at seasonal and spatial scales. The results suggest that the Paris Agreement temperature target of 1.5 °C will be a critical point for WS in SA, which is alarming given that global temperature has already increased by 1 °C compared to the pre-industrial period.

Conclusions

We conclude that global warming of 1.5 °C will cause profound impacts on 875 million people across SA. Hence, sustaining even under this largely anticipated warming target will pose unprecedented challenges to the region, particularly under current water policies, socio-economic paradigms, and population trends. Our results are important in identifying the spatial and temporal hotspots of WS in the region, which will benefit policymakers in designing sustainable water allocation and management policies. While our study represents WS scenarios using most novel data sets, we do agree that including future human interference will further improve WS

estimations. Even though both warming scenarios present a similar degree of WS in terms of the percentage of population affected, a 2 °C warmer world is projected to see an intensification in precipitation and ET. We suggest future work in line with the Paris Agreement 2015 must be carried to investigate both seasonal and temporal changes in the intensification of hydrological fluxes to understand and assess the alterations in the hydrological extremes. We suggest that 1.5 °C of global warming is alarming, particularly for SA and a scenario of water crises can prevail given the extreme population and socio-economic vulnerability of the region. Thus immediate mitigations and legislations are needed to curtail the impact of changing climate on water scarcity, particularly in the hot spots identified in this study.

Datasets and Methods

Scenario Design and Data

In this study, we evaluate WS in SA (India, Pakistan, Bangladesh, Nepal Bhutan, Sri Lanka, and the Maldives) under the Paris Agreement temperature targets of 1.5 and 2 °C temperature increase compared to the pre-industrial period. We also examine the spatial as well as temporal WS hotspots. Further, we evaluate the two important dimensions of WS, availability and consumption, and the hydrological variables and compute their absolute changes compared to the preindustrial period. To do so, we use the outputs from the two global hydrological models (GHMs where the water consumption is available) PCR-GLOBWB^{54,55} and WaterGAP2⁵⁶, forced by three global climate models (GCMs), MIROC5, HadGEM2-ES, and GFDL-ESM2M from Inter-Sectoral Model Intercomparison Project Phase 2b (ISIMIP2b) under the RCP 6.0 middle emission scenario⁴⁶. Thus we generate data for three worlds: one representing natural conditions in the pre-industrial reference period (1661-1860; as mentioned in the ISIMIP protocol with pre-industrial socio-economic conditions fixed at 1860)⁴⁶ and two future scenarios: 1) a 1.5 °C warmer world and 2) a 2 °C warmer world; using the RCP 6.0 middle emission scenario⁴⁶. For the RCP6.0 scenario, future climate and CO₂ concentration vary as per RCP 6.0, while human interferences including land use represent 2005 societal conditions.

We choose the two GHMs specifically because they provide actual water consumption data. Furthermore, we select the three GCMs for the reason that they cross the 1.5 and 2 °C temperature thresholds under RCP 6.0, a prerequisite for this study. The individual GCMs cross the 1.5 and 2 °C temperature thresholds compared to the preindustrial period at different times. For example, a 1.5°C temperature increase is observed in 2056, 2052, and 2032 for GFDL-ESM2M, MIROC5, and HadGEM2-ES, respectively. The time of crossing a warming level is defined as the first time the 31-year running mean of global mean temperature crosses the given thresholds. The threshold represents the central year within this 31-year (i.e., 15 before the level was reached, and 15 after) period (Table S3; <https://www.isimip.org/protocol/isimip2b-temperature-thresholds-and-time-slices/>).

The variables used in this analysis include: water consumption, water availability, precipitation, evapotranspiration (ET), and discharge, all the variables are available from ISIMIP2b at a spatial resolution of 0.50×0.50, except water availability, which is calculated separately. We calculate seasonal water consumption, discharge, and ET for each GCM–GHM combination independently. All the variables are simulated for each season of the year for an average of 31 years, corresponding to the middle of the 31-year temperature time frame of each GCM. Next, we calculate water availability by summing water consumption and discharge from each GCM-GHM combination. Subsequently, we calculate WS as a ratio of water consumption to water availability using water consumption/availability from each GCM-GHM combination. Lastly, we calculate the ensemble mean of all the variables for each warming scenario respectively. Seasonal values represent the average of all the months (mm month⁻¹) in a particular season according to the climatological cycle in SA.

Water scarcity

Water scarcity (WS) refers to the deficit in freshwater resources compared with the environmental or anthropogenic water demand⁴². In this study, water scarcity is estimated as the ratio of actual water consumption to actual water availability in each grid cell for each season following Kummu et al. 2016¹⁶. WS is classified into three categories: 1) WSI<0.2: No Water Scarcity (NWS); 2) WSI=0.2-0.4: Moderate Water Scarcity (MWS); and 3) WSI>0.4: Severe Water Scarcity (SWS).

Here we unequivocally use water consumption, so that the water consumed within a grid cell is no longer available to other users^{16,57}. In SA, due to immense irrigation, a large proportion of water is abstracted^{58–60}; therefore, taking withdrawal might result in overestimation of water scarcity as a part of withdrawal is either available to downstream users or as return flow to the groundwater system^{57,61}.

$$WSI(i,s) = AWC(i,s) / AWA(i,s)$$

Where WSI is the water scarcity index in cell “i” and for the season “s”; AWC (mm/month) is the actual water consumption in cell “i” for the season “s”; and AWA (mm/month) is the actual water available in cell “i” for the season “s”. For example, if more than 40% of the available water is consumed, WS is graded as severe; and similarly, if the consumption ranges between 20-40%, WS is said to be moderate; and when the consumption is less than 20%, there is no WS, the 20% threshold is set based on the amount of water that is required to maintain environmental flows, as identified in the previous studies^{16,43,54,62}. Water consumption (AWC) is the total water consumed by all of the sectors such as agriculture, livestock, domestic, and industrial and the water availability (AWA) is the total amount of water that is available in each grid including the contribution from upstream cells and is calculated for each grid cell by adding total water consumption and discharge. Discharge (mm/month) is the total available water resource in a grid cell (remaining after the upstream and downstream water deduction) including surface and groundwater.

Population under water scarcity

We calculate population under different WS categories for each season of the year for an average of 31 years, corresponding to the middle of the 31-year temperature time frame of each GCM (Table S3) under SSP population distribution, except for the pre-industrial reference period, which corresponds to year-1860 population. We then calculate the ensemble average absolute population and the percentage of the total population under different WS categories in each season of the year for each warming scenario. Thus we show population moving “into” and “out of” the different WS categories seasonally, for example, in JJAS, 157 million (7.6% of the total population in SA)

people are projected to face severe WS, and the number increases to 341 million (16.5%), 610 million (29.4%), and 558 million (28.4%) in ON, DJF, and MAM, respectively in a 1.5 °C warming scenario (Table 1). Results for the 2 °C scenario are shown in supplementary table 2.

We also calculate absolute population and the percentage of the total population under different WS categories in each season of the year for the pre-industrial reference period (supplementary Table 1). Thus we provide the assessment of the increase in the absolute and the percentage of the total population under different WS categories in each warming scenario compared to the pre-industrial period. For example, the total population living under severe WS will increase from 4 (1.5%) to 157 (7.6%), 10.5 (3.7%) to 341 (16.5%), 16 (5%) to 610 (29.4%), and 18 (6%) to 558 (28.4%) million in JJAS, ON, DJF, and MAM, respectively in 1.5 °C warming scenario compared to the preindustrial period.

Hydrological Variables

Here we first perform the individual GCM-GHM simulations for discharge and ET, and only GCM simulations for precipitation for 1.5 and 2 °C warming scenarios, producing 120 datasets (Supplementary Figs 9-14). The analysis is conducted at a seasonal scale and the ensemble projections are then used to show the spatio-temporal alterations in the hydrological variables for both warming scenarios (Supplementary Figs. 2-3). The scenario analysis reveals a significant alteration in the hydrological variables that contributes to the strong seasonality in water availability. We further notice intensification in precipitation and ET in particular under a 2 °C warming scenario. Hence it is important to have a detailed future study focusing on the assessment of hydrological fluxes vis-à-vis hydrological extremes under the Paris Agreement.

Regression Analysis

For linear regression, we consider two climate-driven hydrological fluxes that is precipitation and ET as explanatory variables for WS, given that discharge is one of the parameters in WS assessment (see Equ.1; Methods). Following the methodology of Wu et al 2020⁶³, we use the

following equation to perform regression analysis of seasonal precipitation and ET on WS for both 1.5 and 2 °C warming scenarios.

$$y^* = a_1^* x_1^* + a_2^* x_2^* \quad (2)$$

Where “ y^* ” is the standardized (subtracting the mean and dividing by its standard deviation) seasonal WS, and “ x_i^* ” is the corresponding standardized seasonal precipitation and ET at each grid cell. a_1^* and a_2^* are the partial regression coefficient for precipitation and ET respectively. Only the grid cells with the statistical significance F-test at a 95% confidence level are considered for this analysis. The contribution of different variables (R_i) are calculated as follows:

$$R_i = \frac{|a_i^*|}{\sum_i^N |a_i^*|} * 100\% \quad (3)$$

The contribution of precipitation and ET on the WS is shown in Fig. 3 and Supplementary Fig. 7.

Data availability

The datasets used in this study are obtained from the ISIMIP phase2 framework and are available via www.isimip.org.

Code availability

The code that supports the findings of this study is available at <https://doi.org/10.5281/zenodo.5652805>

Acknowledgments

This work is supported by the Ministry of Science and Technology, Taiwan (MOST) 104-2923-M-002-002-MY4 to the National Taiwan University; by the IGEM project “Impact of Groundwater in Earth system Models”. M.R. acknowledges support from MOST, Taiwan as a part of the Postdoctoral Program (Grant 107-2811-M-002-016 & MOST 108-2811-M-002-501). M.-H. L. and R.-J. W. are supported by the MOST, Taiwan (Grant 110-2628-M-002-004-MY4 and MOST 110-2111-M-002-012)

Author contributions

M.R. and M.H.L. conceived and performed the research. Y.W. and H.M.S provided comments on the manuscript. R.J.W analyzed the ISIMIP2b data with guidance from M.H.L and M.R. Y.W. and H.M.S contributed to the model simulations as a part of the ISIMIP team. M.R and M.H.L drafted the manuscript and all authors contributed to the discussion and interpretation of the results and provided comments on the manuscript.

Competing interests

The authors declare no competing interests.

References

1. IPCC. Global warming of 1.5° C: an IPCC special report on the impacts of global warming of 1.5° C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change. (2018).
2. UNFCCC. The Paris Agreement. United Nations Framework Convention on Climate Change. (2015) http://unfccc.int/paris_agreement/items/9485.php.
3. Alcamo, J., Flörke, M. & Märker, M. Future long-term changes in global water resources driven by socio-economic and climatic changes. *Hydrol. Sci. J.* **52**, 247–275 (2007).
4. Haddeland, I. *et al.* Global water resources affected by human interventions and climate change. *Proc. Natl. Acad. Sci. U. S. A.* **111**, 3251–3256 (2014).
5. Schewe, J. *et al.* Multimodel assessment of water scarcity under climate change. *Proc. Natl. Acad. Sci.* **111**, 3245–3250 (2014).
6. Mekonnen, M. M. & Hoekstra, A. Y. Four billion people facing severe water scarcity. *Sci. Adv.* **2**, e1500323–e1500323 (2016).
7. Veldkamp, T. I. E., Wada, Y., JCH Aerts & Ward, P. J. Towards a global water scarcity risk assessment framework: incorporation of probability distributions and hydro-climatic variability. *Environ. Res. Lett.* **11**, (2016).
8. Hoekstra, A. Y., Mekonnen, M. M., Chapagain, A. K., Mathews, R. E. & Richter, B. D. Global monthly water scarcity: Blue water footprints versus blue water availability. *PLoS One* **7**, (2012).
9. Wada, Y., Van Beek, L. P. H. & Bierkens, M. F. P. Modelling global water stress of the recent past: On the relative importance of trends in water demand and climate variability. *Hydrol. Earth Syst. Sci.* **15**, 3785–3808 (2011).
10. Liu, J. *et al.* Water scarcity assessments in the past, present, and future. *Earth's Futur.* **5**, 545–559 (2017).
11. Vorosmarty, C., Green, P., Salisbury, J. & Lammers, R. Global water resources: vulnerability from climate change and population growth. *Science (80-.).* **289**, 284–288 (2000).
12. Alcamo, J., Flörke, M. & Märker, M. Future long-term changes in global water resources

- driven by socio-economic and climatic changes. *Hydrol. Sci. J.* **52**, 247–275 (2007).
13. Hejazi, M. I. *et al.* Integrated assessment of global water scarcity over the 21st century under multiple climate change mitigation policies. *Hydrol. Earth Syst. Sci.* **18**, 2859–2883 (2014).
  14. Wada, Y. *et al.* Global monthly water stress: 2. Water demand and severity of water stress. *Water Resour. Res.* **47**, 1–17 (2011).
  15. Satoh, Y. *et al.* Multi-model and multi-scenario assessments of Asian water futures: The Water Futures and Solutions (WFaS) initiative. *Earth's Futur.* **5**, 823–852 (2017).
  16. Kummu, M. *et al.* The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability. *Sci. Rep.* **6**, 38495 (2016).
  17. UNWWDP. *The United Nations World Water Development Report: Water for a Sustainable World. Paris, UNESCO.* (2015).
  18. Wada, Y., van Beek, L. P. H., Wanders, N. & Bierkens, M. F. P. Human water consumption intensifies hydrological drought worldwide. *Environ. Res. Lett.* **8**, 034036 (2013).
  19. Gosling, S. N. & Arnell, N. W. A global assessment of the impact of climate change on water scarcity. *Clim. Change* **134**, 371–385 (2016).
  20. Schleussner, C. F. *et al.* Differential climate impacts for policy-relevant limits to global warming: The case of 1.5 °c and 2 °c. *Earth Syst. Dyn.* **7**, 327–351 (2016).
  21. Shiklomanov, I. A. World fresh water resources, in *Water in Crisis*, edited by P.H. Gleick. *Oxford Univ. Press. New York* 13–24 (1993).
  22. Milly, P. C. D., Dunne, K. A. & Vecchia, A. V. Global pattern of trends in streamflow and water availability in a changing climate. *Nature* **438**, 347–350 (2005).
  23. Williams, P. D., Guilyardi, E., Sutton, R., Gregory, J. & Madec, G. A new feedback on climate change from the hydrological cycle. *Geophys. Res. Lett.* **34**, 1–5 (2007).
  24. Sedláček, J. & Knutti, R. Half of the world's population experience robust changes in the water cycle for a 2 °C warmer world. *Environ. Res. Lett.* **9**, 044008 (2014).
  25. Huntington, T. G. Evidence for intensification of the global water cycle: Review and synthesis. *J. Hydrol.* **319**, 83–95 (2006).
  26. Vörösmarty, C. J., Green, P., Salisbury, J. & Lammers, R. Global Water Resources : Vulnerability from Climate Change and Population Growth. *Science (80-.).* **289**, 284–288

- (2000).
27. Scherer, L. & Pfister, S. Dealing with uncertainty in water scarcity footprints. *Environ. Res. Lett.* **11**, 054008 (2016).
  28. Wada, Y., Gleeson, T. & Esnault, L. Wedge approach to water stress. *Nat. Geosci.* **7**, 615–617 (2014).
  29. Wada, B. Y. Reducing water scarcity possible by 2050 : Linking global assessments to policy dimensions. 1–5 (2016) doi:10.1038/ngeo2241.
  30. World Bank Annual Report. 1–18 (2018).
  31. Saeed, F., Schleussner, C.-F. & Ashfaq, M. Deadly heat stress to become commonplace across South Asia already at 1.5°C of global warming. *Geophys. Res. Lett.* (2021) doi:10.1029/2020GL091191.
  32. Singh, R. & Kumar, R. Climate versus demographic controls on water availability across India at 1.5 °C, 2.0 °C and 3.0 °C global warming levels. *Glob. Planet. Change* **177**, 1–9 (2019).
  33. Wada, Y. & Bierkens, M. F. P. Sustainability of global water use: past reconstruction and future projections. *Environ. Res. Lett.* **9**, 104003 (2014).
  34. India, G. Composite Water Management Index: A tool for water management. *Natl. Inst. Transform. India* <http://www.niti.gov.in/writereaddata/files/documen> (2018).
  35. Wada, Y. & Bierkens, M. F. P. Sustainability of global water use: past reconstruction and future projections. *Environ. Res. Lett.* **9**, 104003 (2014).
  36. Asian Development Outlook 2013: Asia’s Energy Challenge. 202–208 (2013).
  37. Oki, T. & Kanae, S. Global Hydrological Cycles and World Water Resources. *Science* (80-.). **313**, 1068–1072 (2006).
  38. Rodell, M., Velicogna, I. & Famiglietti, J. S. Satellite-based estimates of groundwater depletion in India. *Nature* **460**, 999–1002 (2009).
  39. Asoka, A. & Mishra, V. Anthropogenic and Climate Contributions on the Changes in Terrestrial Water Storage in India. *J. Geophys. Res. Atmos.* **125**, 1–21 (2020).
  40. Gerten, D. *et al.* Global Water Availability and Requirements for Future Food Production. *J. Hydrometeorol.* **12**, 885–899 (2011).
  41. KC, S., Wurzer, M., Springer, M. & Lutz, W. Future population and human capital in heterogeneous India. *Proc. Natl. Acad. Sci.* **115**, 8328–8333 (2018).

- 532 42. Veldkamp, T. I. E. *et al.* Water scarcity hotspots travel downstream due to human
533 interventions in the 20th and 21st century. *Nat. Commun.* **8**, 15697 (2017).
- 534 43. Kummu, M., Ward, P. J., de Moel, H. & Varis, O. Is physical water scarcity a new
535 phenomenon? Global assessment of water shortage over the last two millennia. *Environ.*
536 *Res. Lett.* **5**, 034006 (2010).
- 537 44. Konzmann, M. *et al.* Global water resources affected by human interventions and climate
538 change. *Proc. Natl. Acad. Sci.* **111**, 3251–3256 (2013).
- 539 45. Schleussner, C.-F. *et al.* Science and policy characteristics of the Paris Agreement
540 temperature goal. *Nature* **6**, 827–835 (2016).
- 541 46. Frieler, K. *et al.* Assessing the impacts of 1.5 °C global warming – simulation protocol
542 of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b). *Geosci. Model*
543 *Dev.* 4321–4345 (2017) doi:10.5194/gmd-10-4321-2017.
- 544 47. Jin, Q. & Wang, C. A revival of Indian summer monsoon rainfall since 2002. *Nat. Clim.*
545 *Chang.* **7**, 587–594 (2017).
- 546 48. Pflaederer, P., Schleussner, C.-F., Kornhuber, K. & Dim Coumou. Summer weather
547 becomes more persistent in a 2 °C world. *Nat. Clim. Chang.* 666–672 (2019)
548 doi:10.1038/s41558-019-0555-0.
- 549 49. Pascolini-Campbell, M., Reager, J. T., Chandanpurkar, H. A. & Rodell, M. A 10 per cent
550 increase in global land evapotranspiration from 2003 to 2019. *Nature* **593**, 543–547
551 (2021).
- 552 50. Zaveri, E. *et al.* Invisible water, visible impact: Groundwater use and Indian agriculture
553 under climate change. *Environ. Res. Lett.* **11**, (2016).
- 554 51. Asoka, A., Gleeson, T., Wada, Y. & Mishra, V. Relative contribution of monsoon
555 precipitation and pumping to changes in groundwater storage in India. *Nat. Geosci.* **10**,
556 (2017).
- 557 52. Saeed, F., Hagemann, S. & Jacob, D. Impact of irrigation on the South Asian summer
558 monsoon. *Geophys. Res. Lett.* **36**, 1–7 (2009).
- 559 53. Kraaijenbrink, P. D. A., Bierkens, M. F. P., Lutz, A. F. & Immerzeel, W. W. Impact of a
560 1.5 °C global temperature rise on Asia’s glaciers. *Nature* **549**, 257–260 (2017).
- 561 54. Van Beek, L. P. H., Wada, Y. & Bierkens, M. F. P. Global monthly water stress: 1. Water
562 balance and water availability. *Water Resour. Res.* **47**, (2011).

55. Wada, Y., Wisser, D. & Bierkens, M. F. P. Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. *Earth Syst. Dyn.* **5**, 15–40 (2014).
56. Muller Schmied, H. *et al.* Variations of global and continental water balance components as impacted by climate forcing uncertainty and human water use. *Hydrol. Earth Syst. Sci.* **20**, 2877–2898 (2016).
57. Hoekstra, A. Y. & Mekonnen, M. M. The water footprint of humanity. **109**, (2012).
58. Shah, T. Climate change and groundwater: India’s opportunities for mitigation and adaptation. *Environ. Res. Lett.* **4**, 1–13 (2009).
59. Jain, M. *et al.* Groundwater depletion will reduce cropping intensity in India. *Sci. Adv.* **7**, 1–10 (2021).
60. Shekhar, S. *et al.* Modelling water levels of northwestern India in response to improved irrigation use efficiency. *Sci. Rep.* 1–15 (2020) doi:10.1038/s41598-020-70416-0.
61. Kendy, E., Conservancy, T. N. & Measures, C. P. The False Promise of Sustainable Pumping Rates. *Ground Water* **41**, 2–4 (2003).
62. Falkenmark, M. *et al.* On the Verge of a New Water Scarcity: A Call for Good Governance and Human Ingenuity. *SIWI Policy Br.* 20 (2007).
63. Wu, W. Y. *et al.* Divergent effects of climate change on future groundwater availability in key mid-latitude aquifers. *Nat. Commun.* **11**, 1–9 (2020).

Table and Figure captions:

Table 1 shows the seasonal distribution of the South Asian population (in millions) under various WS categories at 1.5 °C temperature increase under RCP 6.0 and SSP2 climate and population projections. SWS refers to severe water scarcity, MWS refers to moderate water scarcity, and the total water scarcity is the sum of SWS and MWS. The population projections correspond to the central year of the 31-year mean corresponding to the individual GCM temperature threshold as shown in table S3.

Figure 1. Water scarcity (measured as water scarcity index- WSI) in South Asia at 1.5 °C temperature increase under RCP 6.0 (a) Seasonal ensemble mean absolute changes in WS at 1.5 °C (b) Seasonal ensemble mean absolute changes in WS at 1.5 °C compared to pre-industrial period. The ensemble represents the seasonal averaged WS from the individual GHM-GCM combination. WSI is calculated as a ratio of water consumption (mm month⁻¹) to water availability (mm month⁻¹).

Figure 2. Water availability and water consumption in South Asia at 1.5 °C temperature increase under RCP 6.0 scenario (a) The ensemble mean absolute changes in the seasonal water availability compared to the pre-industrial period. (b) The ensemble mean absolute changes in the seasonal water consumption compared to the pre-industrial period. All the variables are represented as an ensemble, averaged over each season (mm month⁻¹) from individual GHM-GCM combinations.

Figure 3. Contribution of precipitation and ET on WS in South Asia as derived from regression analysis at 1.5 °C of temperature increase under RCP 6.0 scenario (a) Spatiotemporal control of precipitation on WS. (b) Spatiotemporal control of ET on WS.

Table 1 shows the seasonal distribution of the South Asian population (in millions) under various WS categories at 1.5 °C temperature increase under RCP 6.0 and SSP2 climate and population projections. SWS refers to severe water scarcity, MWS refers to moderate water scarcity, and the total water scarcity is the sum of SWS and MWS. The population projections correspond to the central year of the 31-year mean corresponding to the individual GCM temperature threshold as shown in table S3.

	Water Scarcity Grade	Winter (DJF)		Pre Monsoon (MAM)		Monsoon (JJAS)		Post Monsoon (ON)	
		Population (millions)	Percentage of the total population	Population (millions)	Percentage of the total population	Population (millions)	Percentage of the total population	Population (millions)	Percentage of the total population
Bhutan	SWS	0	0	0	0	0	0	0	0
	MWS	0	0	0	0	0	0	0	0
Bangladesh	SWS	50	27.9	38	21.0	0	0	1.8	1.0
	MWS	28	15.8	29	16.3	5.7	3.2	8	4.7
India	SWS	494	31.3	503	31.8	129	8.1	278	17.6
	MWS	209	13.2	217	13.7	143	9.1	202	12.8
Pakistan	SWS	64	24.8	47	18.1	25	9.8	61	24.2
	MWS	27	10.2	21	8.1	30	11.7	28	11.0
Nepal	SWS	0.98	2.8	0.98	2.8	0	0	0	0
	MWS	0	0	0	0	0	0	0	0
Sri Lanka	SWS	0.62	3.5	0.37	2.1	2.50	14.1	0.5	2.8
	MWS	0.50	2.8	1	5.6	1.8	9.9	0.7	4.0
South Asia	SWS	610	29.4	588	28.4	157	7.6	341	16.5
	MWS	265	12.8	268	13.0	181	8.7	239	11.5
	Total	875	42.2	856	41.4	338	16.3	580	28

629   **Figure 1. Water scarcity (measured as water scarcity index- WSI) in South Asia at 1.5 °C**
630   **temperature increase under RCP 6.0 (a) Seasonal ensemble mean absolute changes in WS at**
631   **1.5 °C (b) Seasonal ensemble mean absolute changes in WS at 1.5 °C compared to pre-**
632   **industrial period. The ensemble represents the seasonal averaged WS from the individual**
633   **GHM-GCM combination. WSI is calculated as a ratio of water consumption (mm month⁻¹)**
634   **to water availability (mm month⁻¹).**

Figure 2. Water availability and water consumption in South Asia at 1.5 °C temperature increase under RCP 6.0 scenario (a) The ensemble mean absolute changes in the seasonal water availability compared to the pre-industrial period. (b) The ensemble mean absolute changes in the seasonal water consumption compared to the pre-industrial period. All the variables are represented as an ensemble, averaged over each season (mm month⁻¹) from individual GHM-GCM combinations.

657 **Figure 3. Contribution of precipitation and ET on WS in South Asia as derived from**
 658 **regression analysis at 1.5 °C of temperature increase under RCP 6.0 scenario (a)**
 659 **Spatiotemporal control of precipitation on WS. (b) Spatiotemporal control of ET on WS.**

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SI.pdf](#)