Supplementary Information

Supplementary Notes

Falkenmark Indicator for water scarcity assessment

The Falkenmark indicator (Falkenmark, 1989) for water scarcity is a commonly used metric to assess the availability of freshwater resources relative to the population's water needs. The indicator is calculated by dividing the total available water resources in a region by the population living in that region. Falkenmark Indicator is a ratio of a country's water footprint to its total renewable water resources which are a measure of both ground and surface water (blue water) and moisture stored in soil strata (green water) (Vanham et al., 2022; Damkjaer and Taylor, 2017). It relates the total freshwater resources with the total population in a country and indicates the pressure that the population puts on water resources, including the need for natural ecosystems. The higher the index, the more pressure a country faces on its water resources.

The threshold value of 1000 m^3 per person per year, often associated with the Falkenmark indicator, represents a benchmark for water scarcity. When the annual renewable water resources fall below this threshold, it suggests that the region is experiencing water scarcity. Such a threshold is used in many publications, e.g. Schewe et al. (2013) provided an multimodel assessment of water scarcity under climate change with this thresholder (another thresholder of 500 m^3 per capita per year is used to show an extreme water scarcity situation).

Since the conception of the water scarcity indicator, different arguments have been proposed as the basis for the setting of thresholds of 'water stress' and 'water scarcity'. Notwithstanding the separate rationales for the thresholds of water stress and water scarcity, the values of 1700 and 1000 m^3 $capita^{-1}$ $year^{-1}$ have been uncritically adopted and assimilated in the mainstream literature without an empirical basis.

Here are the different thresholds commonly used in the Falkenmark indicator for different level of water stress:

(1) Less than 1,000 m^3 per capita per year: This is the most commonly used threshold in the Falkenmark indicator. It indicates that the annual renewable water resources available per person are below the 1,000 m^3 threshold, suggesting high water stress and potential water scarcity.

(2) 1,000 to 1,700 m^3 per capita per year: This range is sometimes considered as moderate water stress. It signifies that the annual renewable water resources per person fall within

this range, indicating a moderate level of water availability but still highlighting potential water stress.

(3) Higher than 1,700 per capita per year: This range is generally associated with low to no water stress. It suggests that the annual renewable water resources per person are relatively abundant, indicating sufficient water availability for most needs.

Hydrologists typically assess scarcity by looking at the population-water equation. An area is experiencing water stress when annual water supplies drop below 1,700 m^3 per person. When annual water supplies drop below 1,000 m^3 per person, the population faces water scarcity, and below 500 m^3 absolute scarcity (https://www.un.org/waterforlifedecade/scarcity.shtml). Because this paper discusses water scarcity rather than water stress, the threshold of 1000 m3 is used. Noted that we showed the main results with thresholds of 1000 m3, and we also compared the results with 500 and 1700 in the supplementary materials.

This 1000 m^3 per person per year don't represent water necessary for personal use, and a man does not need 1000 m^3 water per year only for personal use. Falkenmark et al. (1989) divided the pressure on water resources into five levels based on the population supported by 1 million cubic meters of water resources. In 1992, they officially proposed to use the per capita water resource amount as the water stress index to measure the degree of regional water scarcity. They determined the threshold of water resource pressure based on the per capita water demand of moderately developed countries in arid regions.

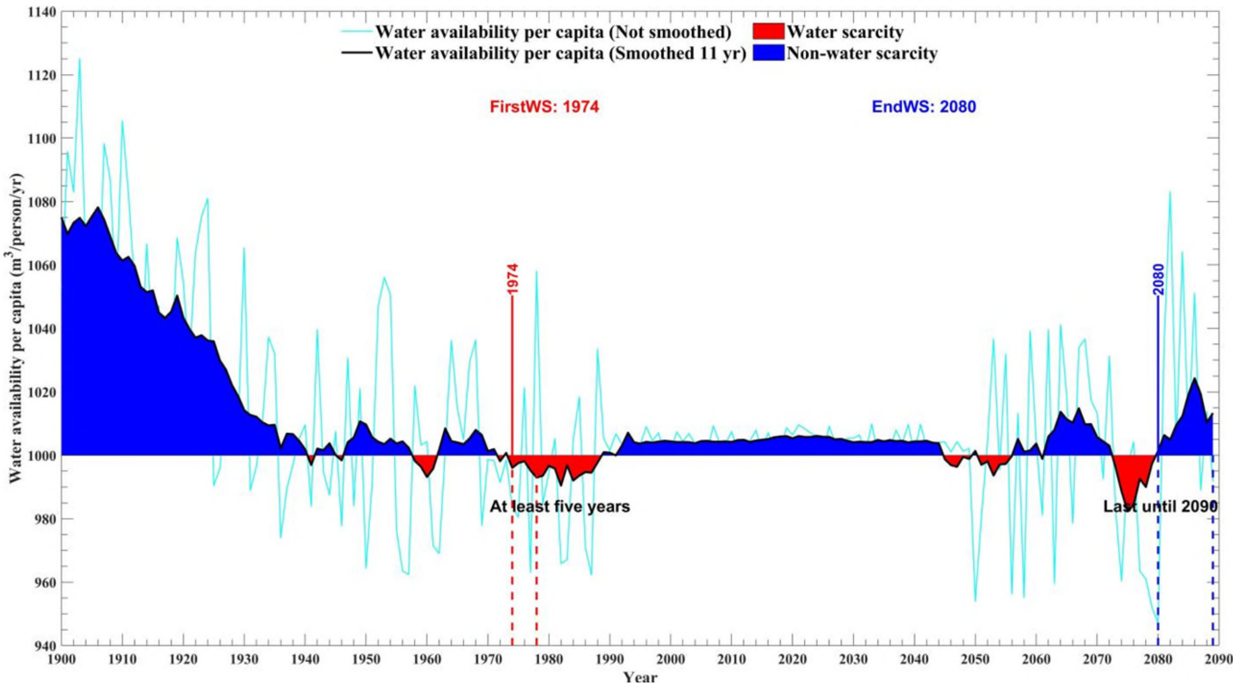
This indicator does not represent water that needed for agriculture; it is not applicable to areas dominated by irrigated agriculture (where are indeed conservative). However, reasons for the wide acceptance of this indicator are due to its simple and intuitive, and data on human population are readily available.

The Falkenmark indicator serves as a simplified measure to gauge water scarcity and provides a starting point for understanding water availability relative to population needs. However, it has limitations in capturing all dimensions of water scarcity, including water quality, accessibility, and distribution, which are vital aspects to consider in assessing water stress. Moreover, regional factors, climate conditions, and water management practices significantly influence water availability and usage patterns. The variations in water use efficiency and technologies across regions play a significant role in determining the level of water scarcity experienced. It is important to acknowledge that a fixed threshold of 1000 m^3 per person per year may not fully account for these variations. For instance, countries like Israel and other developed nations with high-efficiency water use technologies may require lower thresholds to indicate water scarcity compared to regions that employ less efficient practices. Additionally, socio-economic development directly impacts water scarcity and should be considered in assessments. Therefore, it is crucial to interpret the threshold within the specific regional context and consider other relevant indicators and factors when evaluating water scarcity.

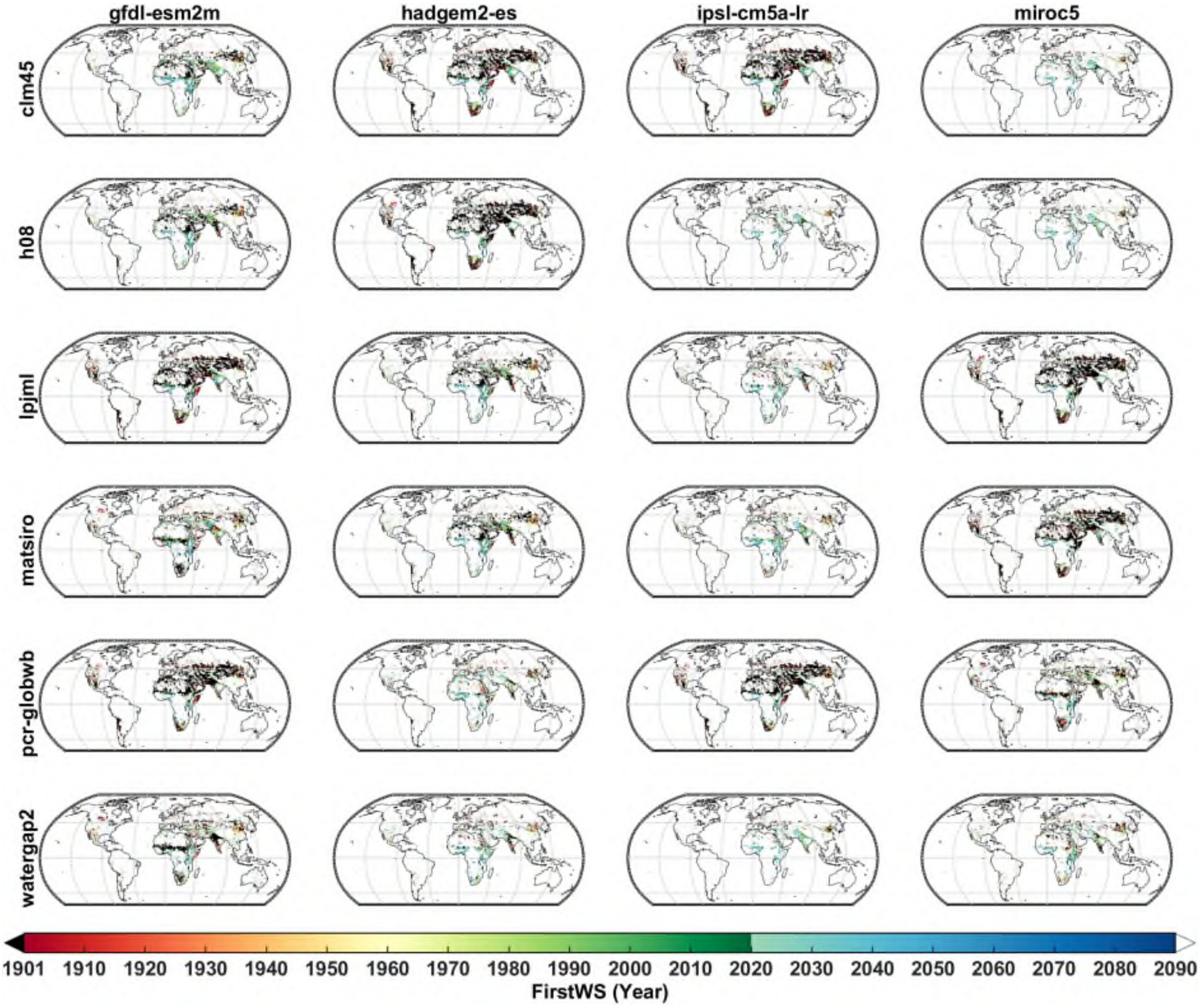
Reference:

Falkenmark, M., Lundqvist, J. & Widstrand, C. Macro-scale water scarcity requires micro-scale approaches. Nat. Res. Forum 13(4), 258–267 (1989).
Schewe, J. et al. Multimodel assessment of water scarcity under climate change. Proc. Natl. Acad. Sci. USA 111, 3245-3250 (2013).
Simon Damkjaer and Richard Taylor. The measurement of water scarcity: Defining a meaningful indicator. Ambio 46(5): 513–531 (2017).
Vanham, D., Alfieri, L. & Feyen, L. National water shortage for low to high environmental flow protection. Scientific Reports 12, 3037, doi:10.1038/s41598-022-06978-y (2022).

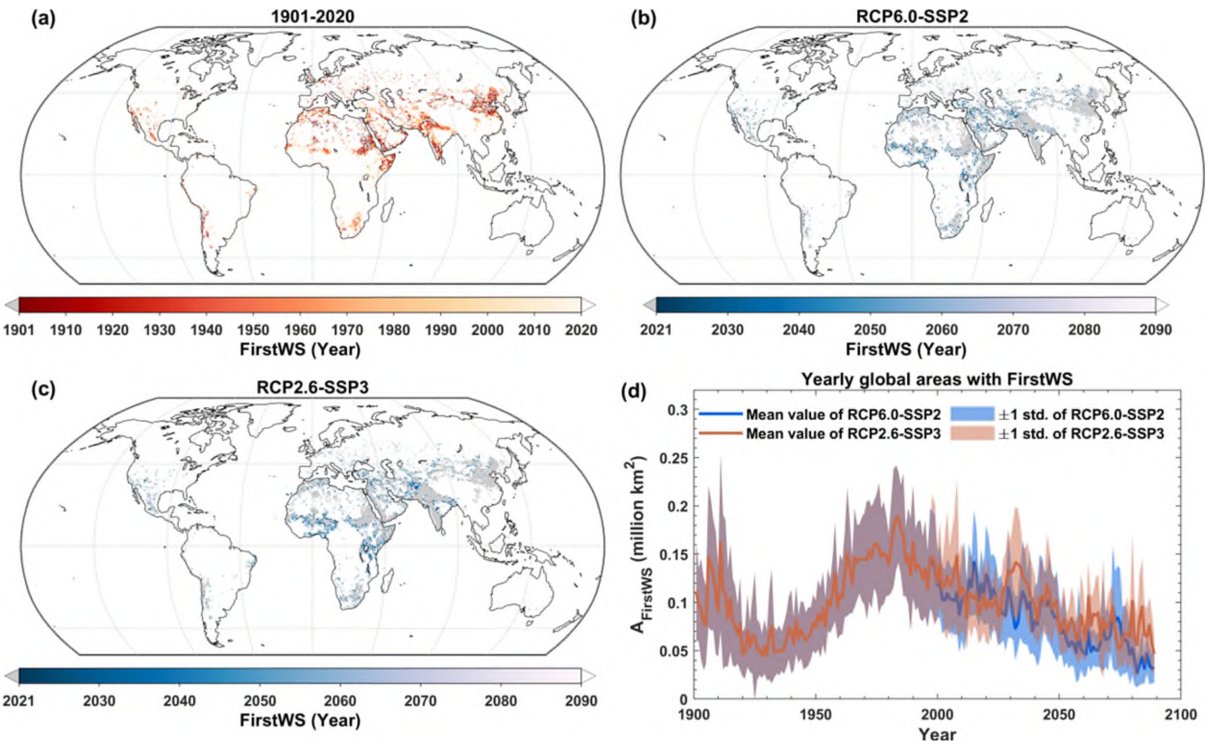
Supplementary Figure



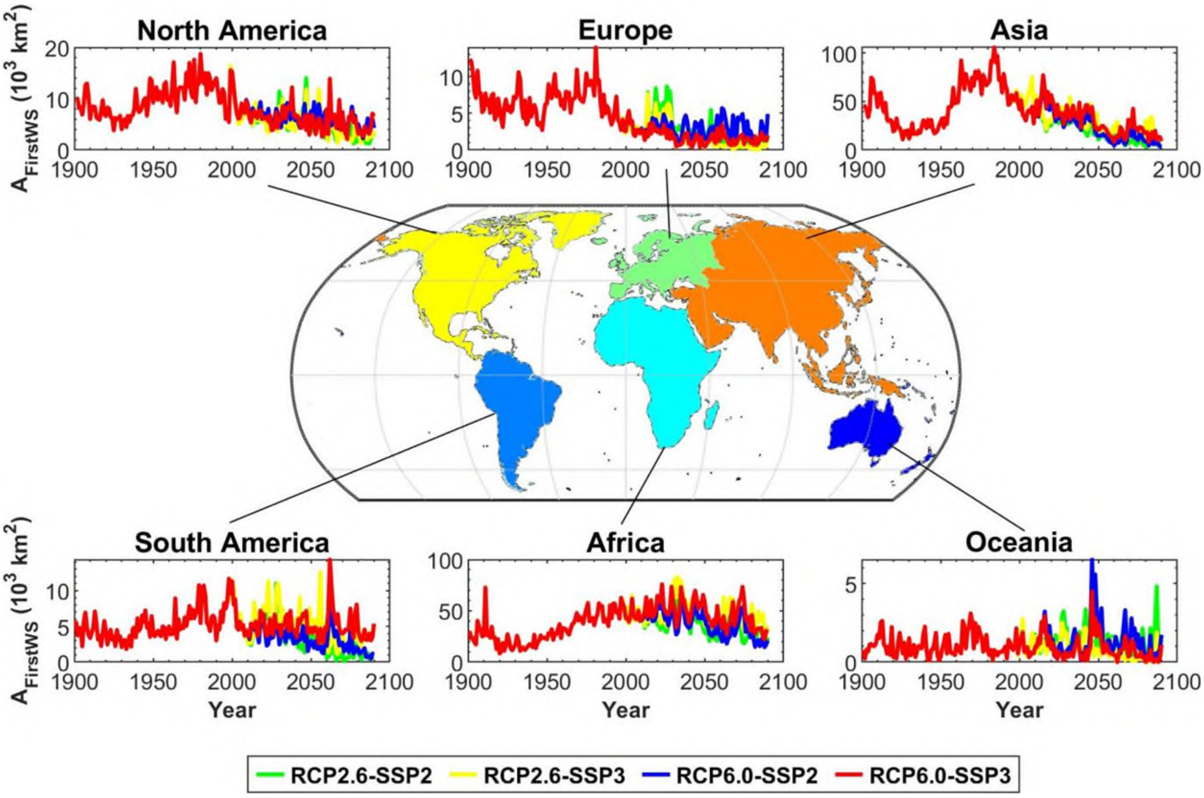
Supplementary Fig. 1. Schematic diagram for the identification of the FirstWS and EndWS. The first occurrence time for water scarcity (FirstWS) is defined here as the first year when per capita water resources are less than a threshold of 1,000 m^3/person/yr for at least five consecutive years. The disappearing time of water scarcity (EndWS) is defined as the situation that per capita water resources relieved from water scarcity, and will last until 2090.



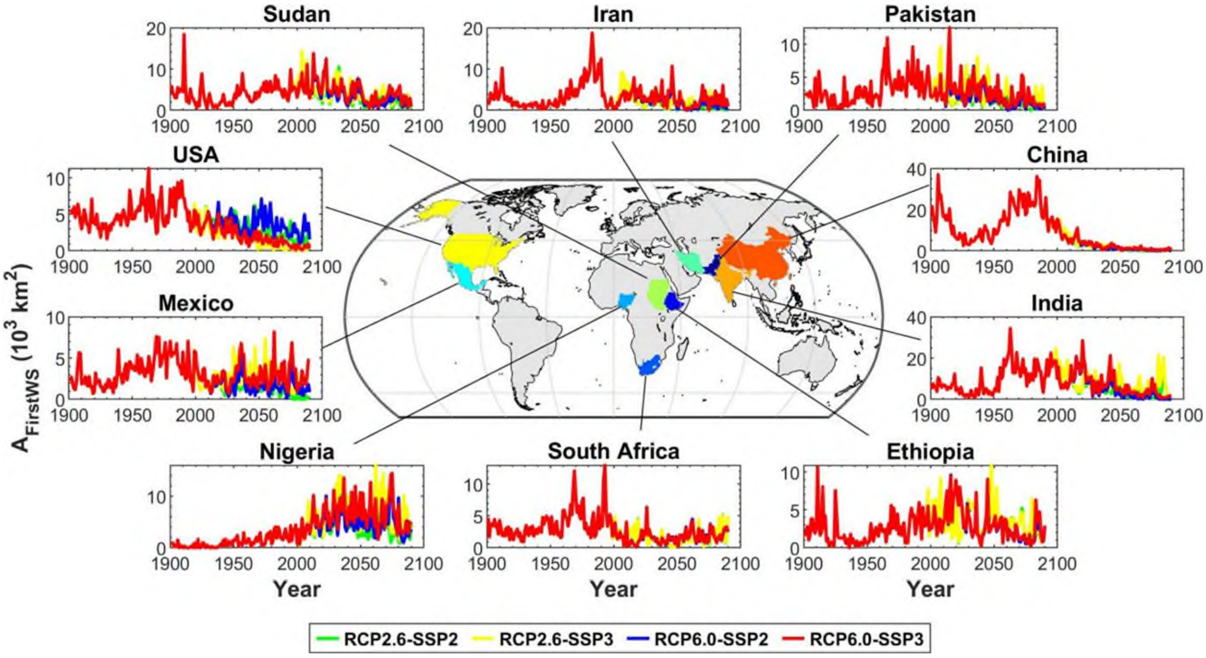
Supplementary Fig. 2. The spatial distributions of the first occurrence time for water scarcity (FirstWS) from 1901 to 2090 for 24 different Global Hydrological Models (GHMs) - General Circulation Models (GCMs) combinations. Note that here we only show the results of RCP2.6-SSP2 scenario combination. The FirstWS was produced by using 11-year running-mean water availability per capita and the threshold of 1000 m^3/person/yr. The black color means that the water scarcity have occurred prior to 1901. The white areas indicate that the median year of FirstWS does not occur by 2090.



Supplementary Fig. 3. The spatial distributions of multi-model ensemble median year of the first occurring time for water scarcity (FirstWS) for 1901-2090. The median year of FirstWS was projected by 24 Global Hydrological Models (GHMs) - General Circulation Models (GCMs) combinations in (a) Historical period (1901-2020); (b) future period (2021-2090) under RCP2.6-SSP2 combination; (c) future period under water availability RCP6.0-SSP3; (d) Yearly first occurring water scarcity areas ($A_{FirstWS}$) for1901-2090. In (a), the dark areas mean that the water scarcity have occurred in 1900 and the white areas represent that water scarcity has not occurred before the year 2020. In (b) and (c), the red areas mean that the water scarcity have occurred in before 2020 and the white areas represent that water scarcity will never occur before the year 2090.

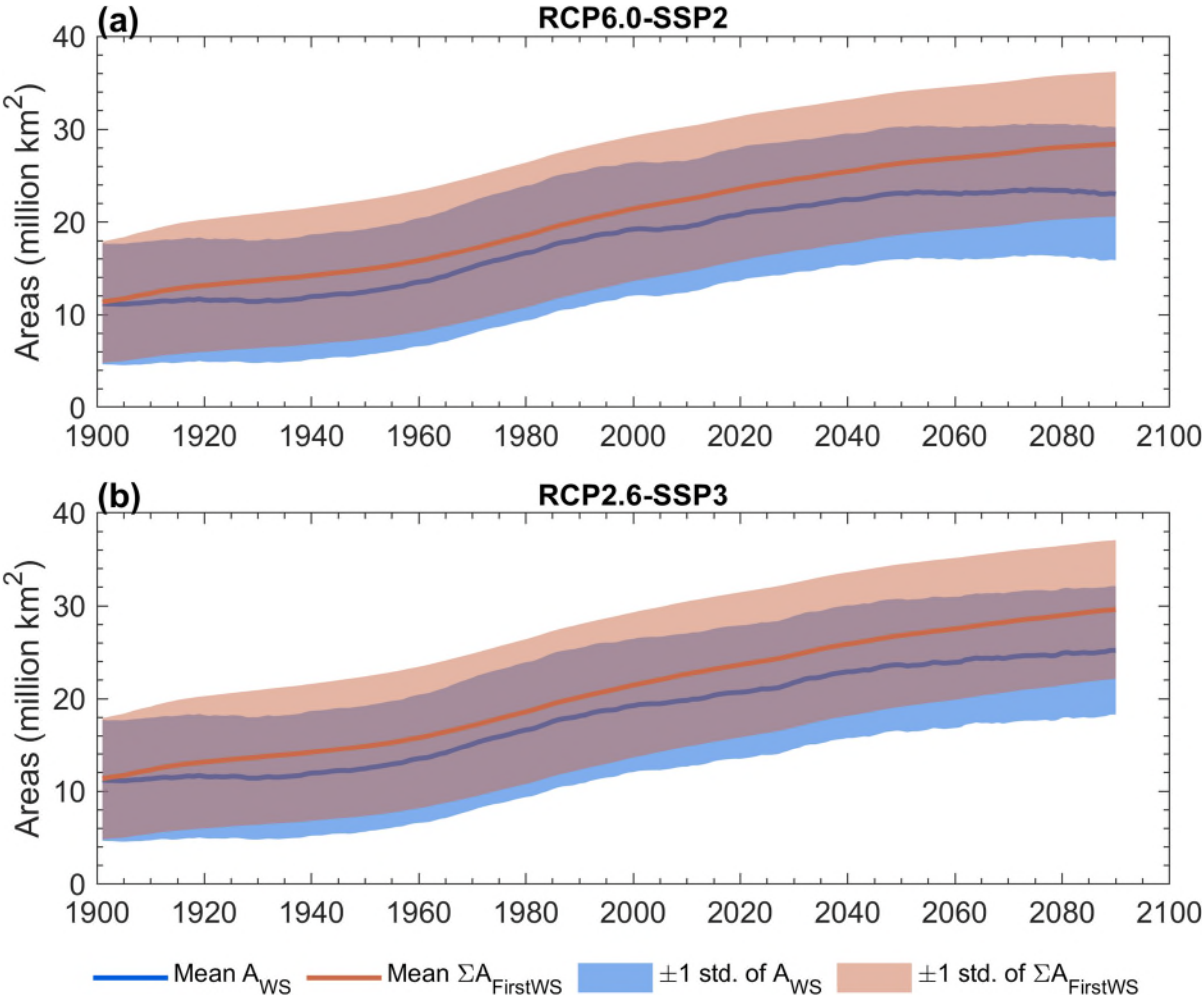


Supplementary Fig. 4. Annual total area with FirstWS ($A_{FirstWS}$) aggregated over the six continents. Hence the ensemble mean of 24 different Global Hydrological Models (GHMs) - General Circulation Models (GCMs) combinations was used to plot the figure, and the areas have been produced with the mean of 24 models' ensembles.

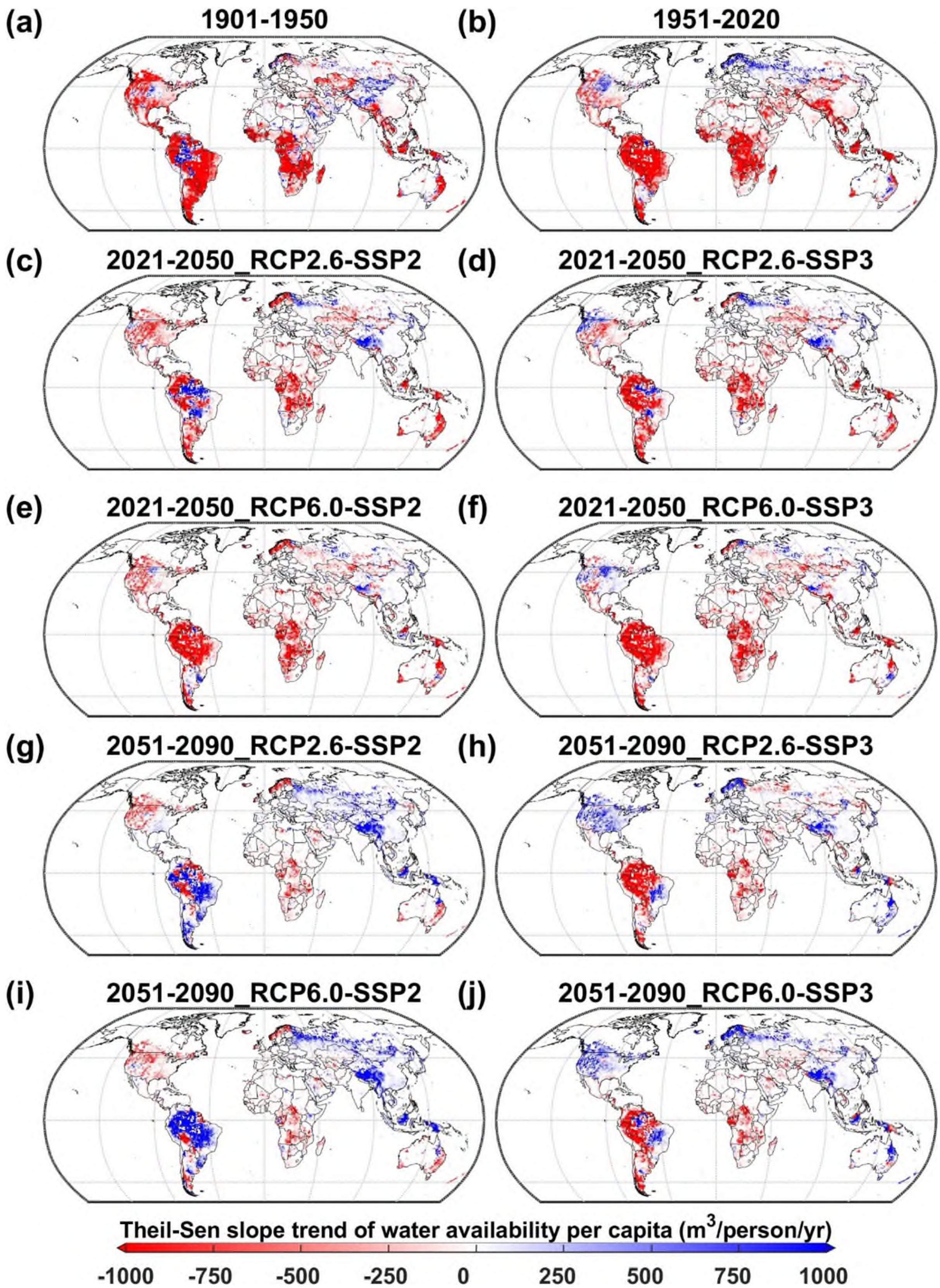


Supplementary Fig. 5. Multi-model ensemble mean of $A_{FirstWS}$ for different countries.

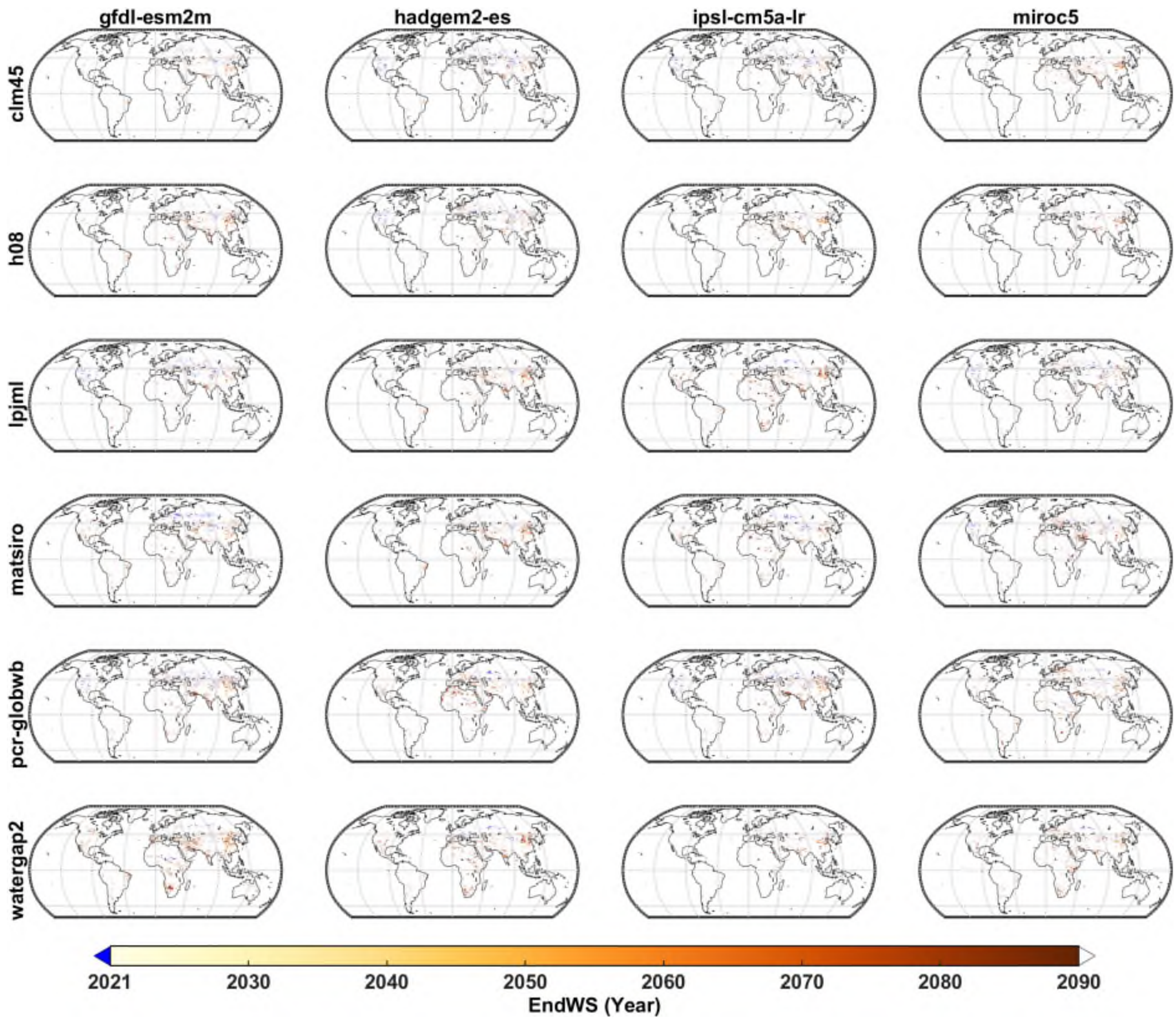
Note the top 10 countries with the highest $A_{FirstWS}$ over 1901-2090 for the RCP2.6-SSP2 are selected. The value is the mean of 24 models' ensembles.



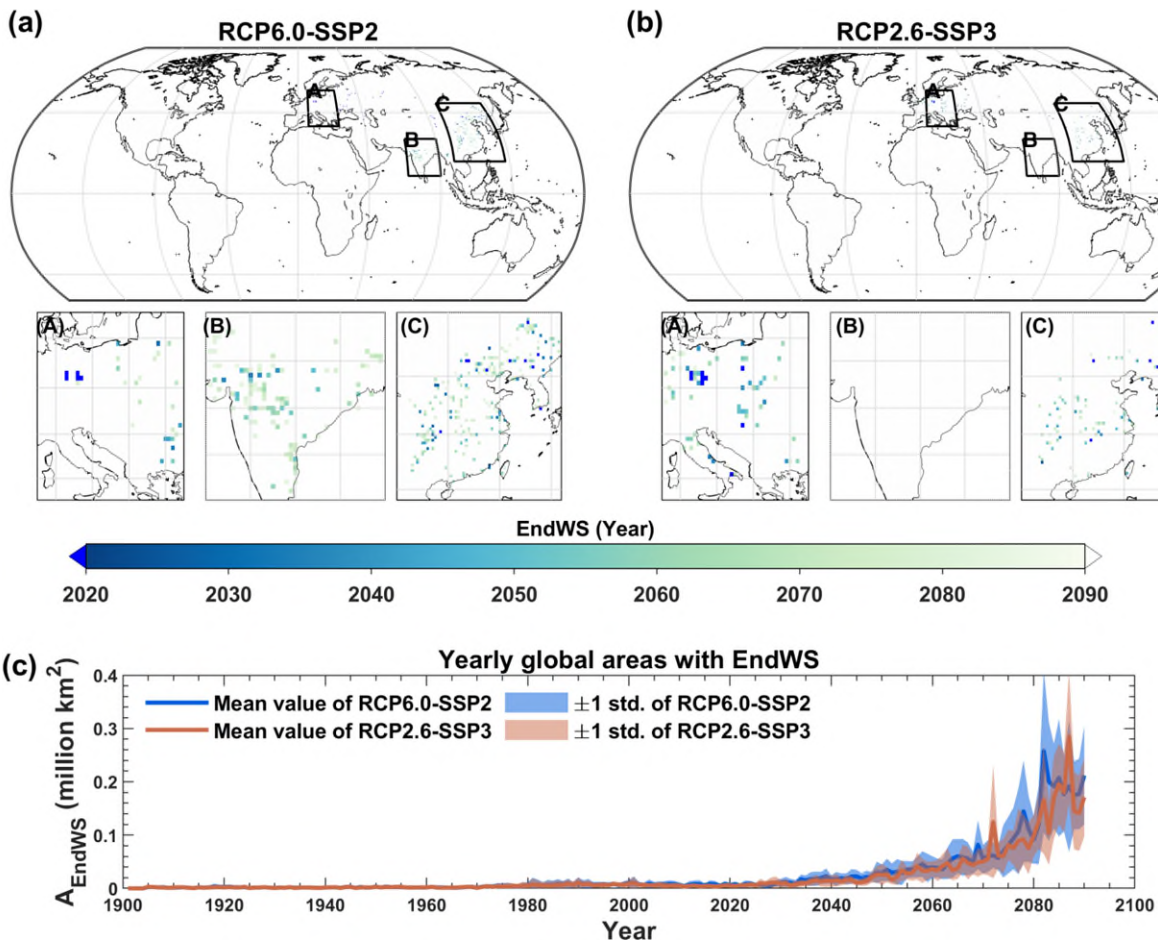
Supplementary Fig. 6. The multi-model ensemble means of global water scarcity areas (A_{WS}) and cumulative areas with FirstWS ($\sum A_{FirstWS}$) from 1901 to 2090. (a) water availability (RCP6.0), Population (SSP2); (b) water availability (RCP2.6), Population (SSP3). The shadow shows the standard deviations of A_{ws} and $\sum A_{FirstWS}$ among 24 Global Hydrological Models (GHMs) - General Circulation Models (GCMs) combinations.



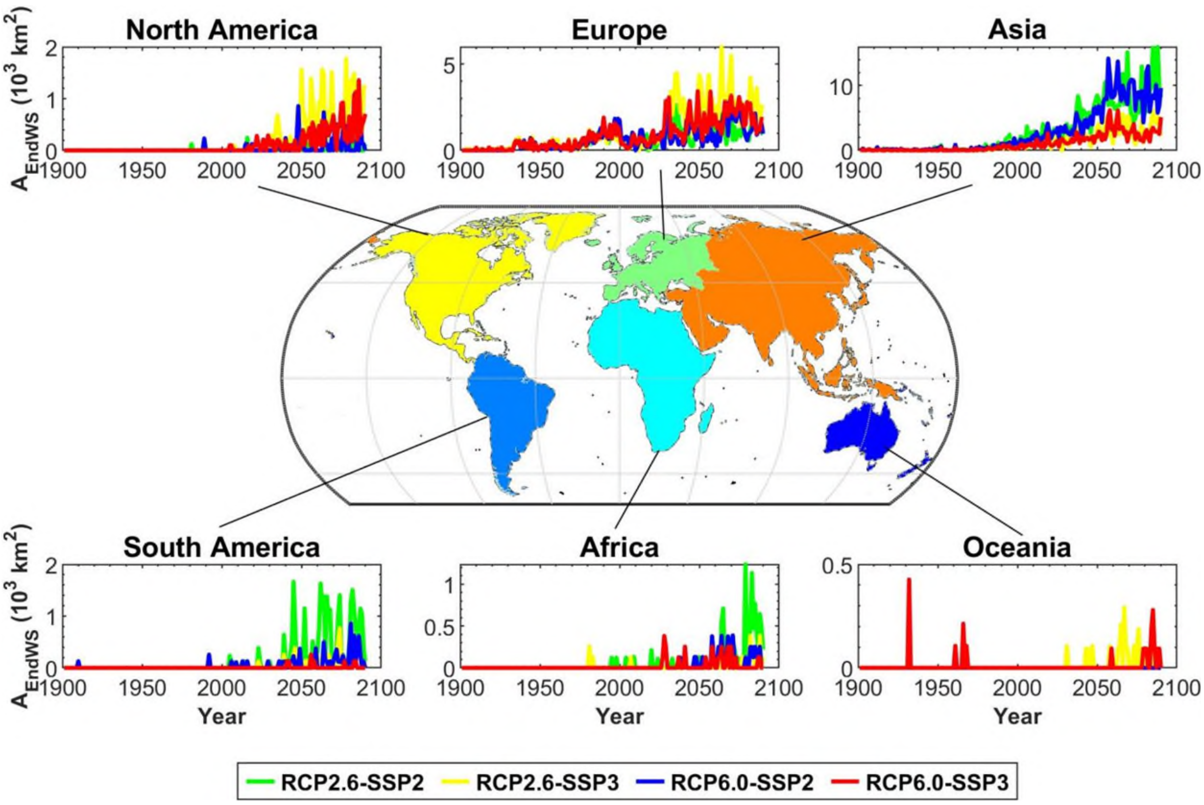
Supplementary Fig. 7. The Theil-Sen slope of water availability per capita for different periods and scenarios. The Theil-Sen slope of water availability per capita for (a) historical periods during 1901-1950; (b) historical periods during 1951-2020; (c) future scenario during 2021-2050 under RCP2.6-SSP2 combination; (d) future scenario during 2021-2050 under RCP2.6-SSP3 combination; (e) future scenario during 2021-2050 under RCP6.0-SSP2 combination; (f) future scenario during 2021-2050 under RCP6.0-SSP3 combination; (g) future scenario during 2051-2090 under RCP2.6-SSP2 combination; (h) future scenario during 2051-2090 under RCP2.6-SSP3 combination; (i) future scenario during 2051-2090 under RCP6.0-SSP2 combination; (j) future scenario during 2051-2090 under RCP6.0-SSP3 combination. The multi-model ensemble means of 24 Global Hydrological Models (GHMs) - General Circulation Models (GCMs) combinations are used to calculate water availability firstly. The white cover shows no significant trend at 0.05 level according to the seasonal Mann-Kendall test.



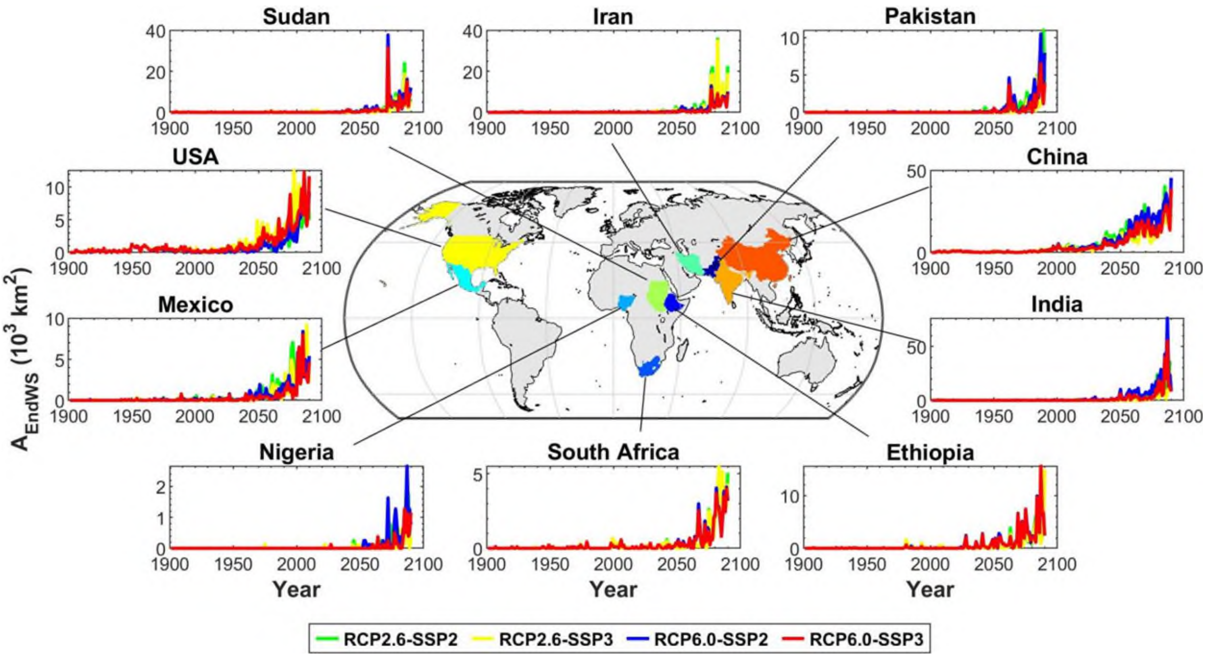
Supplementary Fig. 8. The spatial distributions of the first disappearing time for water scarcity (EndWS) from 1901 to 2090 for 24 different Global Hydrological Models (GHMs) - General Circulation Models (GCMs) combinations. Note that here we only show the results of RCP2.6-SSP2 scenario combination. The EndWS was produced by using 11-year running-mean water availability per capita and the threshold of 1000 m^3/person/yr. The white areas indicate that the median year of EndWS does not occur by 2090.



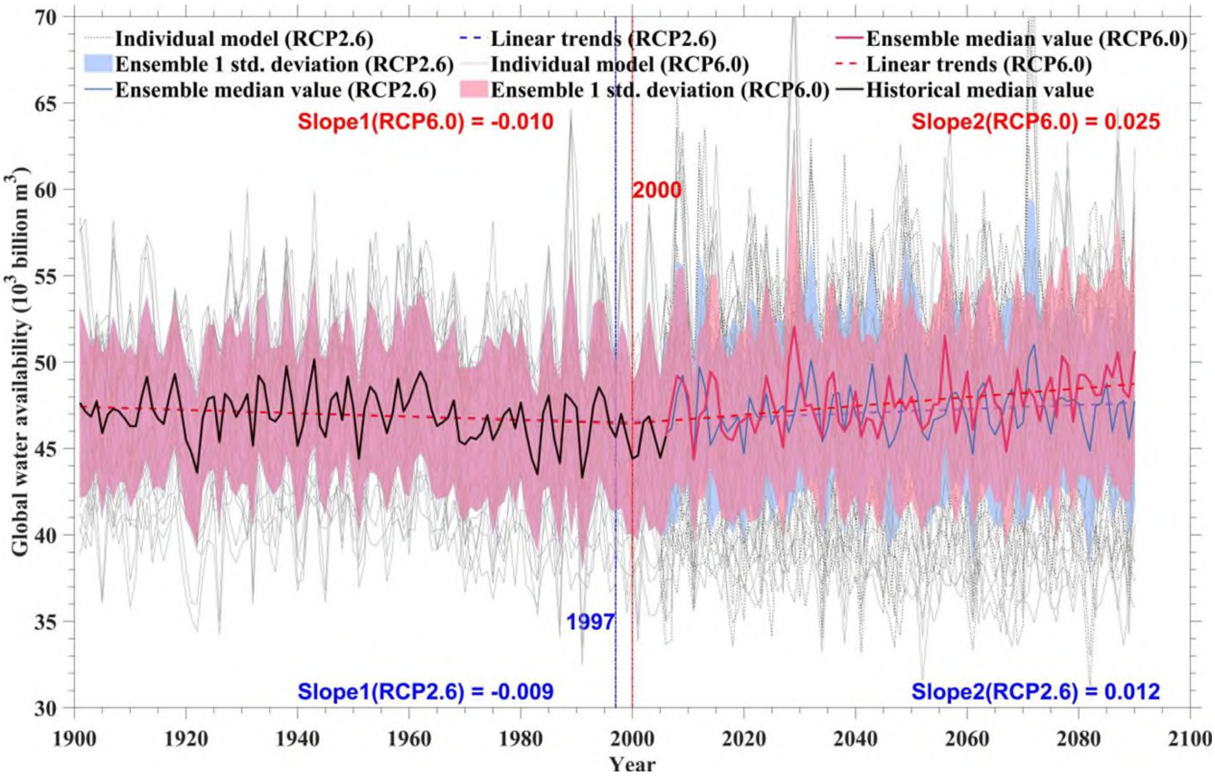
Supplementary Fig. 9. The spatial distributions of multi-model ensemble median year of first disappearing time for water scarcity (EndWS). The mean year of EndWS was calculated when no less than 1/3 of the 24 Global Hydrological Models (GHMs) - General Circulation Models (GCMs) combinations show EndWS. **(a)** RCP6.0-SSP2 scenario. (b) RCP2.6-SSP3 scenario. (c) Annual global area for a specific year when EndWS is reached (A_{EndWS}). The white areas in (a) and (b) represent that EndWS will never occur before 2090.



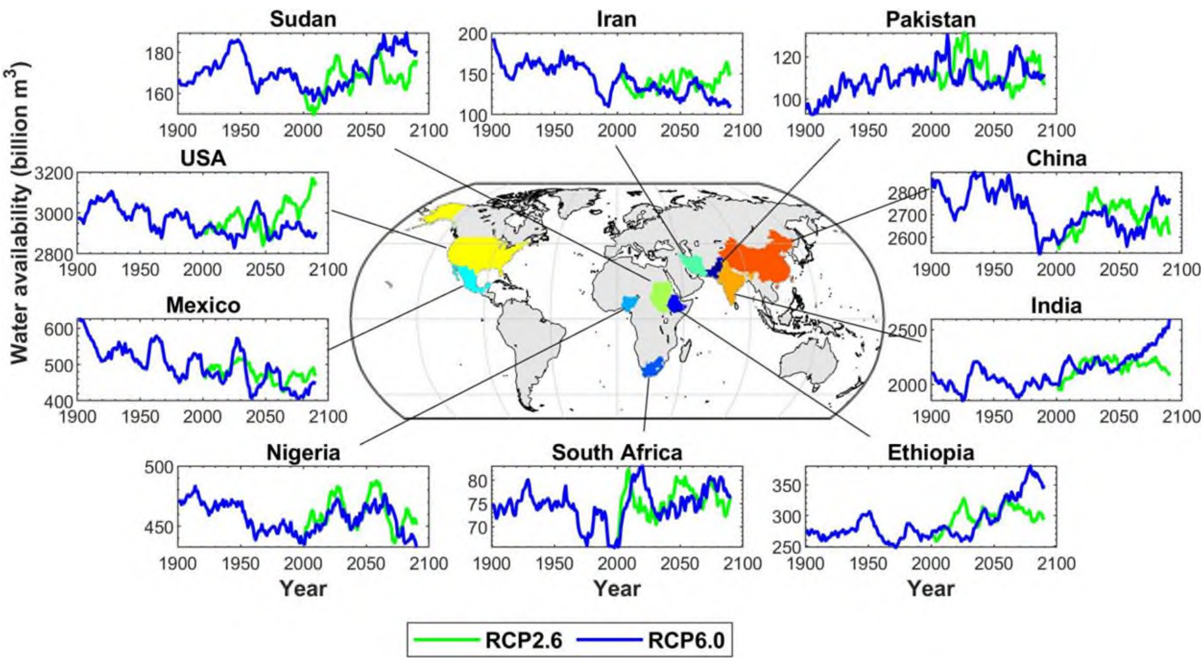
Supplementary Fig. 10. Annual total area of first disappearing water scarcity (A_{EndWS}) aggregated over the six continental regions. For future scenarios, climate scenarios are RCP2.6 and RCP6.0, and population scenarios are SSP2 and SSP3. The value is the mean of 24 models ensembles.



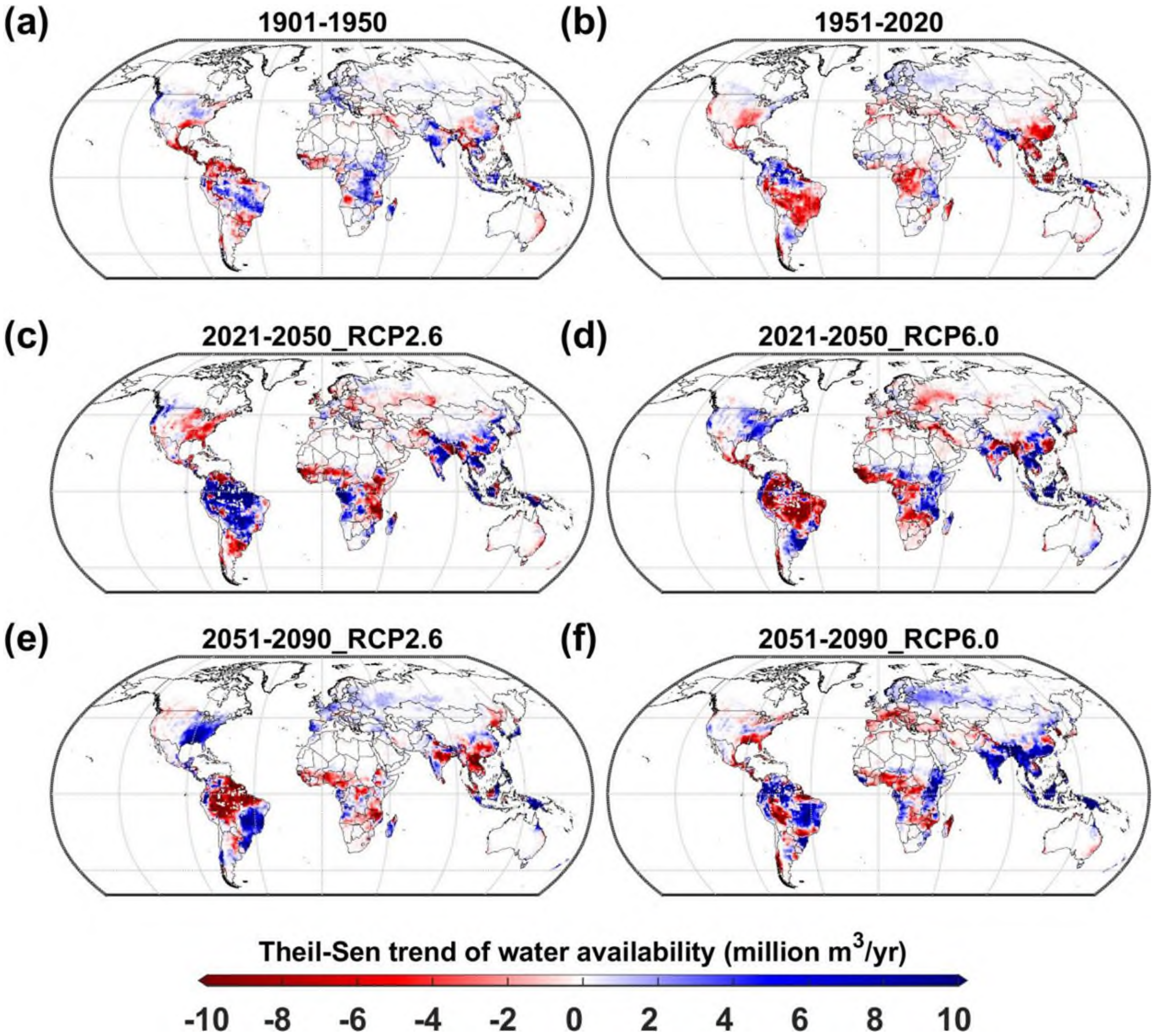
Supplementary Fig. 11. Annual total area of first disappearing water scarcity (A_{EndWS}) aggregated among countries. The top ten countries are selected with the largest $A_{FirstWS}$ from 1901 to 2090. The value is the mean of 24 models ensembles.



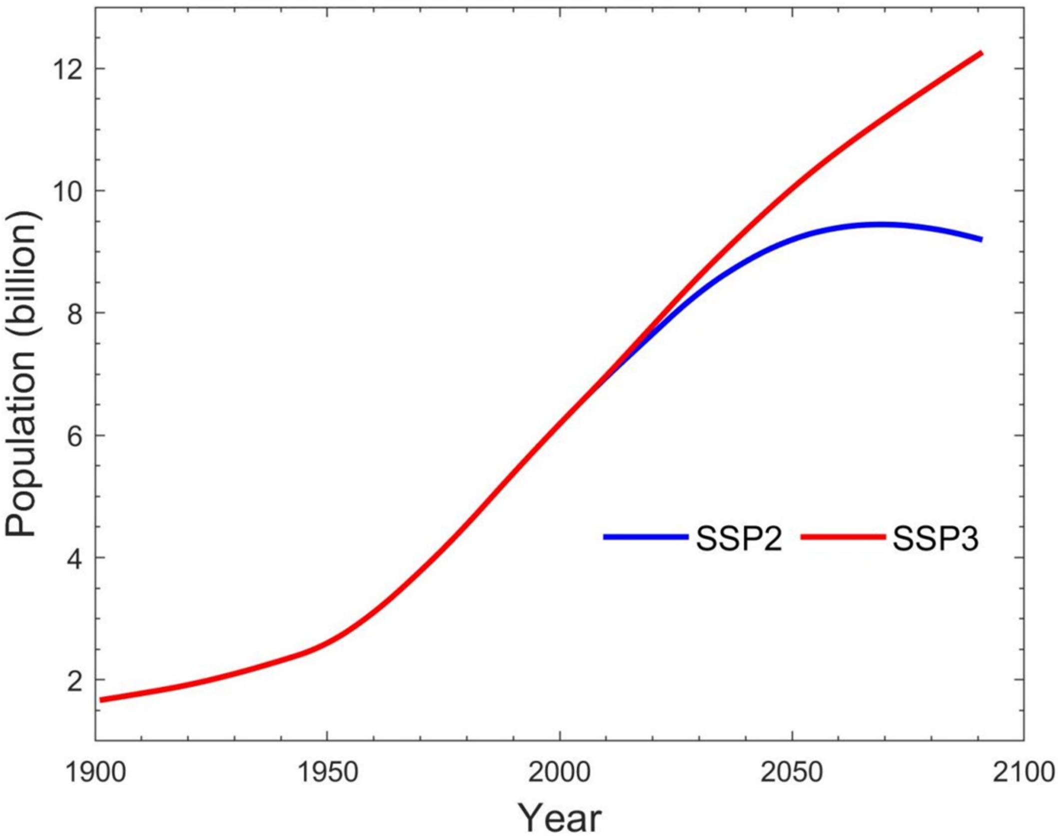
Supplementary Fig. 12. Projected global total water availability under RCP2.6 and RCP6.0 from 1901 to 2090.



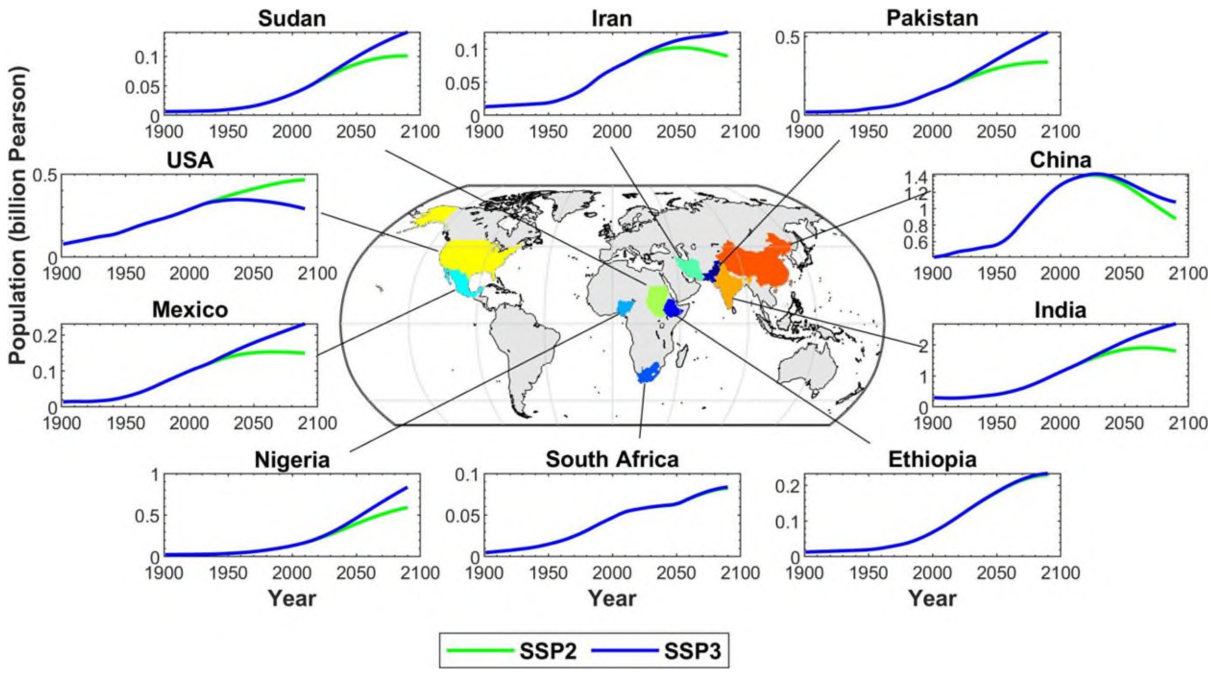
Supplementary Fig. 13. Yearly water availability aggregated over the top ten countries from 1901 to 2090. The ten countries were selected according to the most ten cumulative areas crossed FirstWS from 1901 to 2090. For future scenarios, climate scenarios are RCP2.6 and RCP6.0. Note that the water availability has been produced with using 3-year running-mean. The value is the mean of 24 models ensembles.



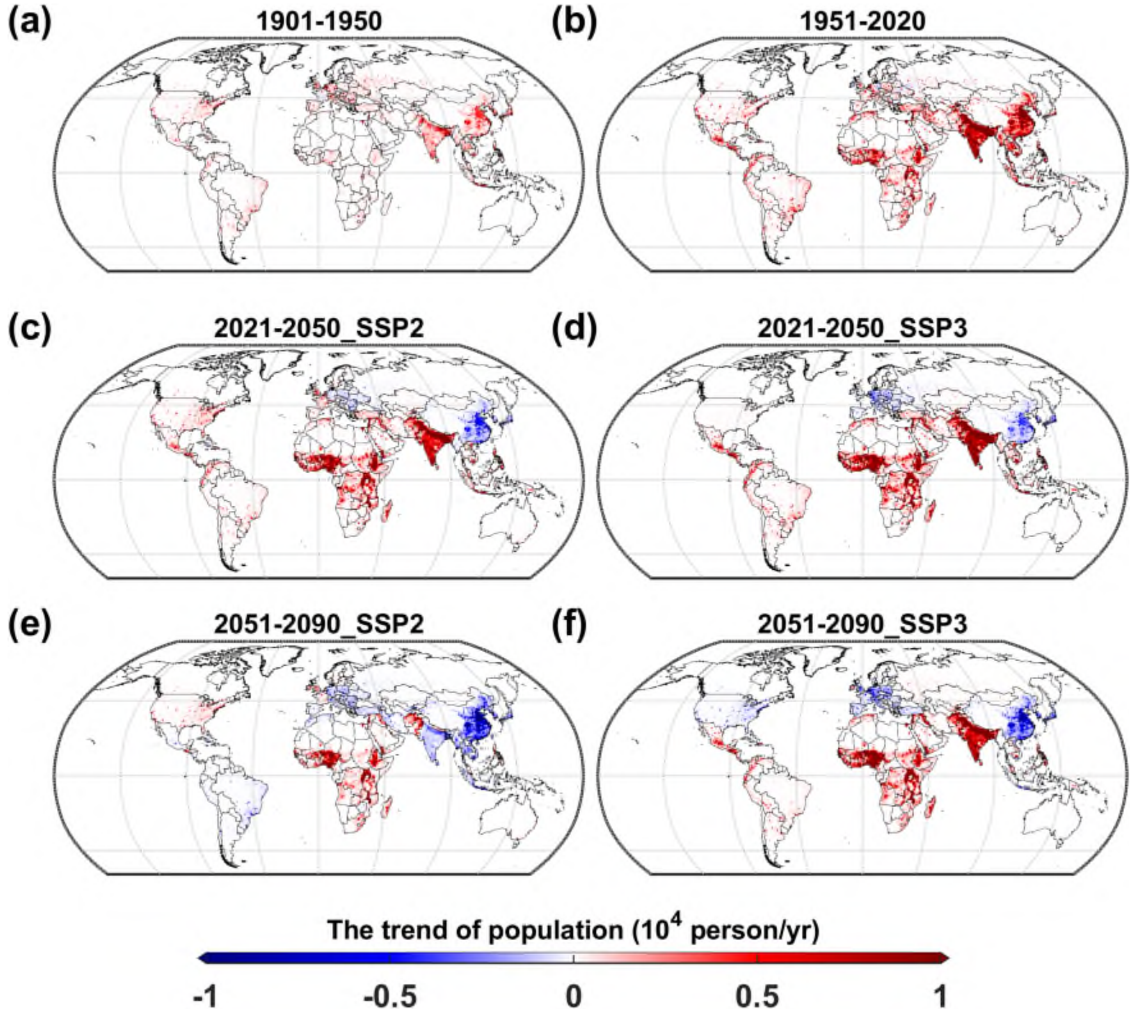
Supplementary Fig. 14. The trend of water availability from 1901 to 2090. The Theil-Sen slope of water availability for (a) historical periods during 1901-1950; (b) historical periods during 1951-2020; (c) future scenario during 2021-2050 under RCP2.6; (d) future scenario during 2021-2050 under RCP6.0; (e) future scenario during 2051-2090 under RCP2.6; (f) future scenario during 2051-2090 under RCP6.0. Regions without significant trend at 0.05 level according to the seasonal Mann-Kendall test was masked to white. The mean water availability was first calculated among 24 Global Hydrological Models (GHMs) - General Circulation Models (GCMs) combinations, then the changing trend of water availability was estimated.



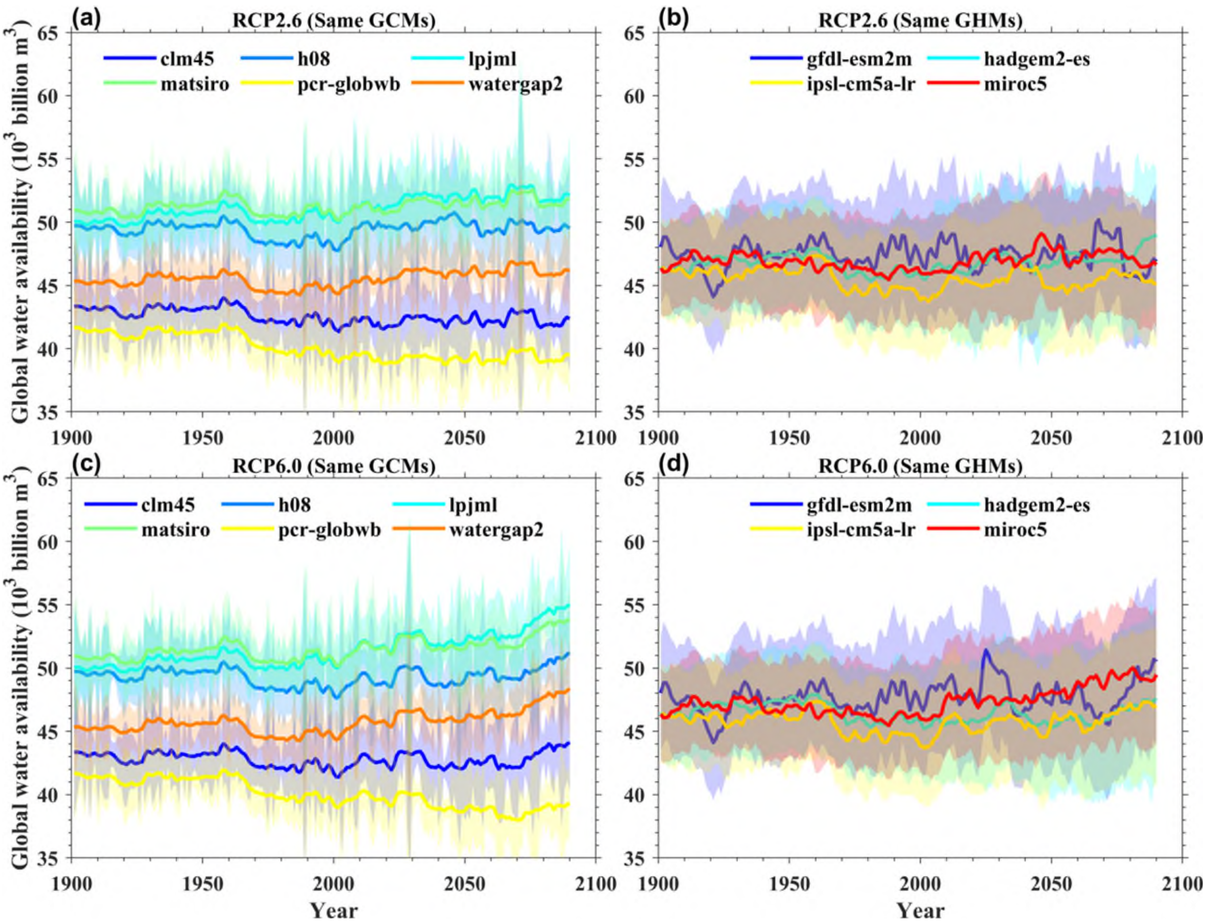
Supplementary Fig. 15. Projected global total population under SSP2 and SSP3 from 1901 to 2090.



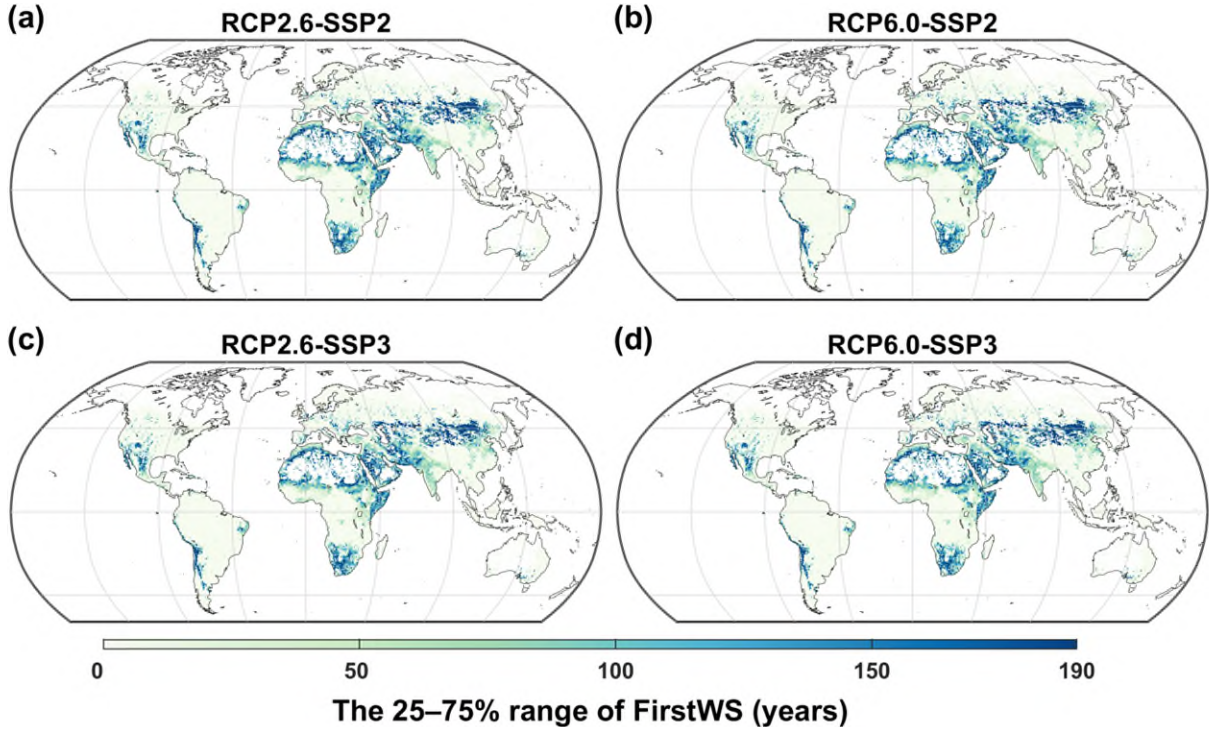
Supplementary Fig. 16. Yearly population aggregated over the top ten countries from 1901 to 2090. The ten countries were selected according to the most ten cumulative areas crossed FirstWS from 1901 to 2090. For future scenarios, population scenarios are SSP2 and SSP3.



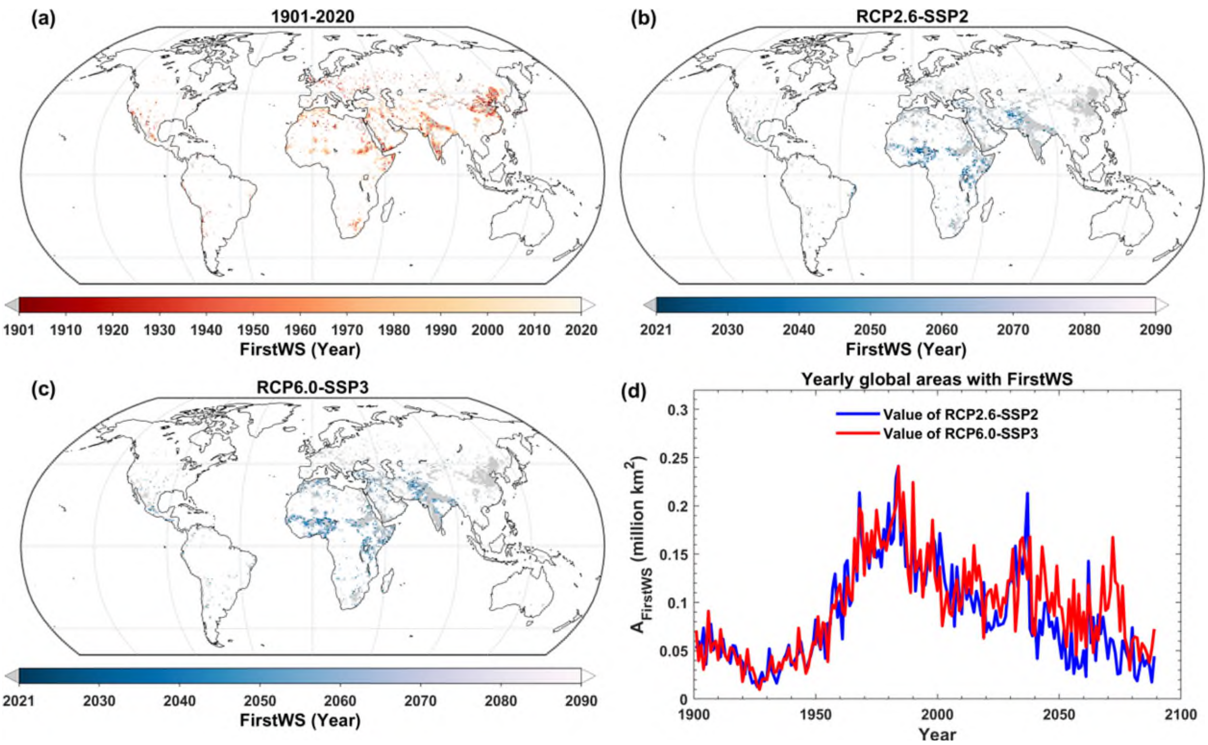
Supplementary Fig. 17. The mean trend of population for four different stages from 1901 to 2090. The Theil-Sen slope of population for (a) historical periods during 1901-1950; (b) historical periods during 1951-2020; (c) future scenario during 2021-2050 under SSP2; (d) future scenario during 2021-2050 under SSP3; (e) future scenario during 2051-2090 under SSP2; (f) future scenario during 2051-2090 under SSP3. Regions without significant trend at 0.05 level according to the seasonal Mann-Kendall test was masked to white.



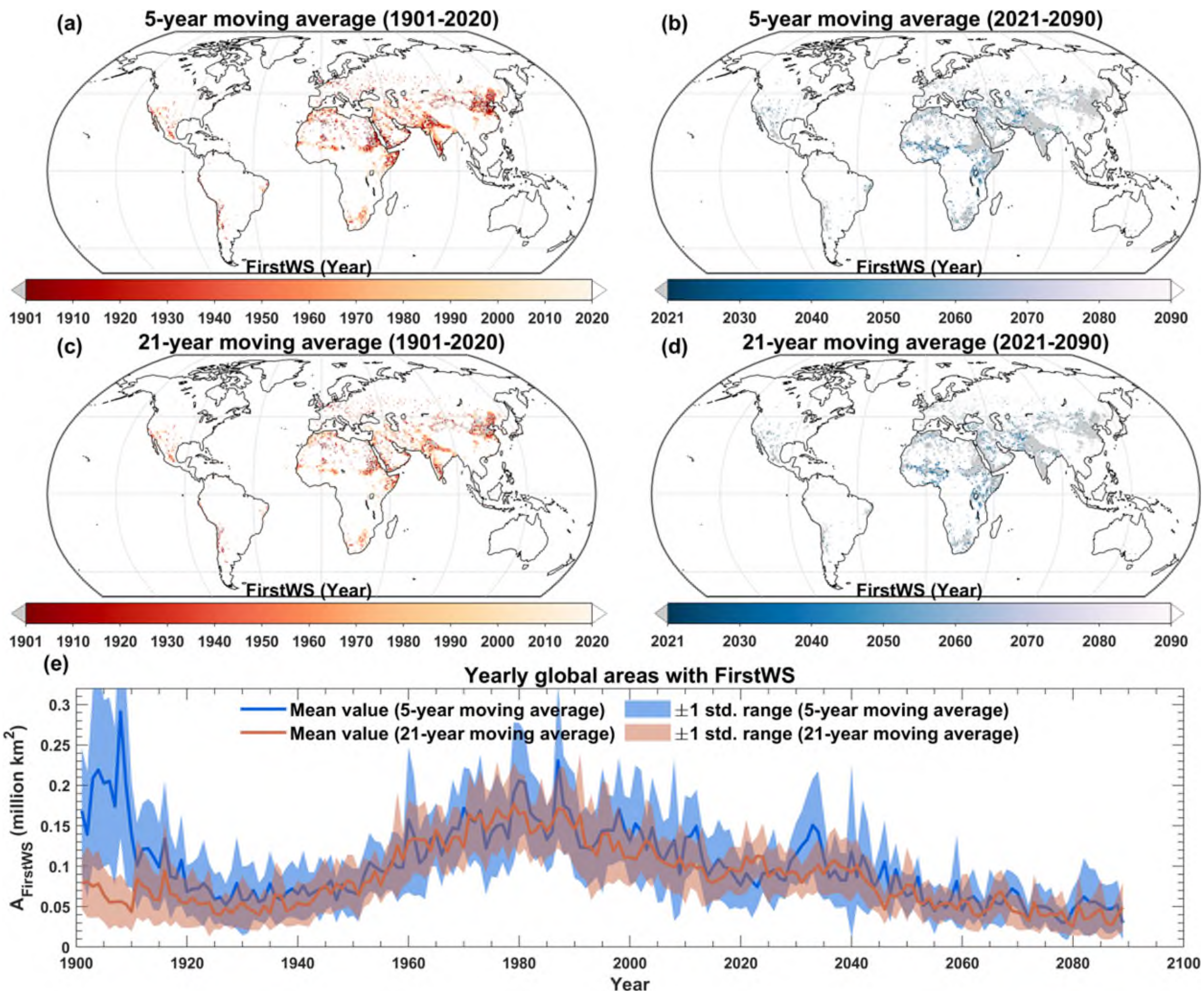
Supplementary Fig. 18. The reorganization the ISIMIP2b-derived runoff according to General Circulation Models (GCMs) types or Global Hydrological Models (GHMs) types. (a) the uncertainty of six GHMs (here fix the GCMs by averaging four GCMs) in RCP 2.6; (b) the uncertainty of four GCMs (here fix the GHMs by averaging six GHMs) in RCP2.6; (c) the uncertainty of six GHMs (here fix the GCMs by averaging four GCMs) in RCP 6.0; (d) the uncertainty of four GCMs (here fix the GHMs by averaging six GHMs) in RCP6.0.



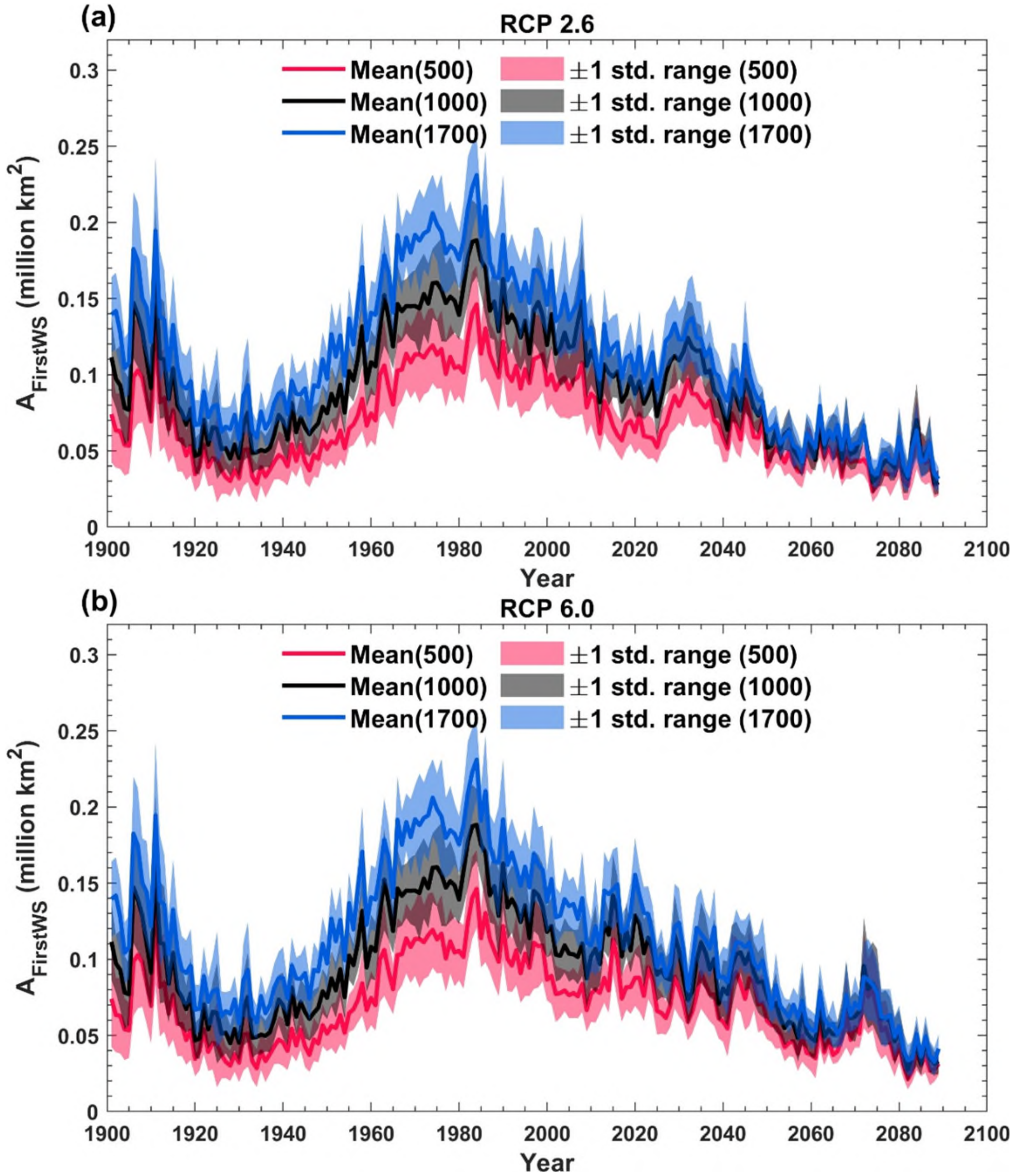
Supplementary Fig. 19. **The spatial distributions of 25%-75% range years of multi-model ensembles of the first occurring time for water scarcity (FirstWS) from 1901 to 2090.** The 25%-75% range years of FirstWS were estimated under (a) water availability (RCP2.6), population (SSP2); (b) water availability (RCP6.0), population (SSP2); (c) water availability (RCP2.6), population (SSP3); (d) water availability (RCP6.0), population (SSP3). The gray regions are uninhabited regions.



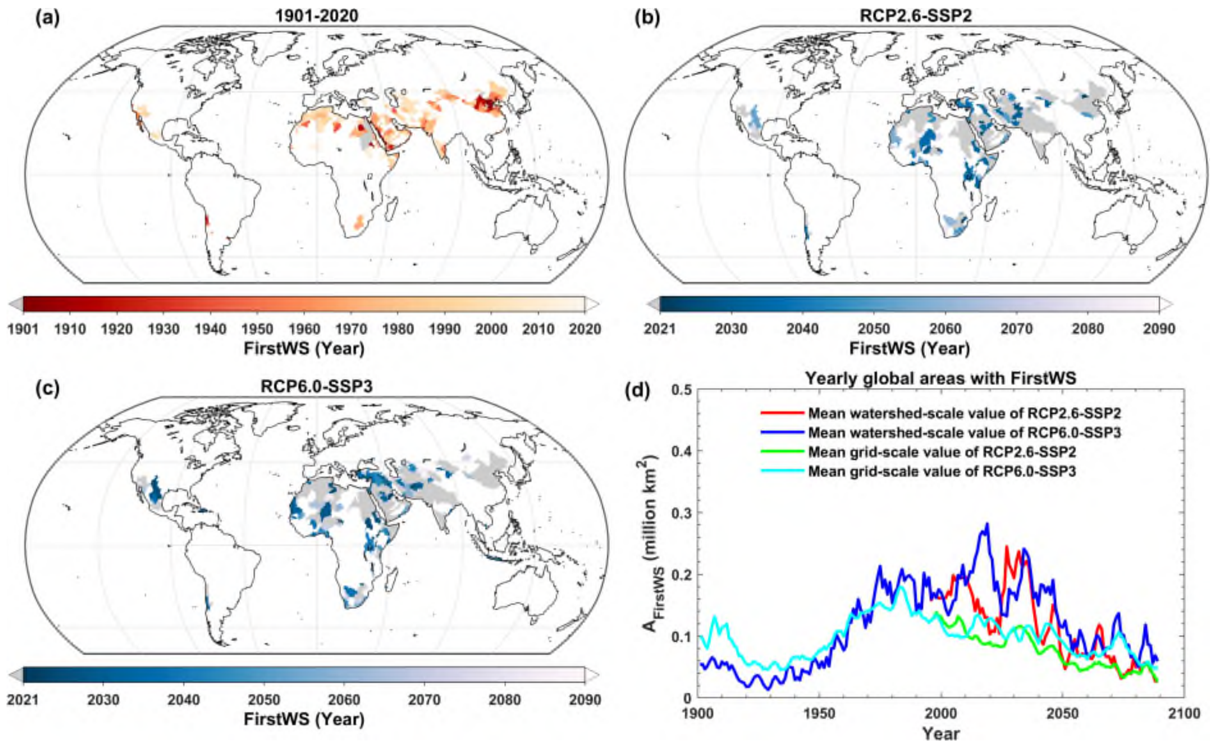
Supplementary Fig. 20. The spatial distributions of the first occurrence time for water scarcity (FirstWS). The map is the same as **Figure 2** in the main text, but the difference is that we first calculated the mean of 24 Global Hydrological Models (GHMs) - General Circulation Models (GCMs) combinations of water availability per capita and subsequently estimated FirstWS directly. (a) Historical periods (1901-2020); (b) future periods (2021-2090) under RCP2.6-SSP2 combination; (c) future periods under RCP6.0-SSP3 combination; (d) The annual global area for a specific year when FirstWS is reached ($A_{FirstWS}$). In (a), the dark red color indicates that water scarcity occurred before 1901 and the white color indicates that water scarcity has never occurred in the historical period. In (b) and (c), the black color means that water scarcity occurs before 2021. The white color indicates that water scarcity never occurs before 2090. The gray areas represent uninhabited regions. This map was produced with the threshold of 1000 m^3/person/yr and smoothed with 11-year running window.



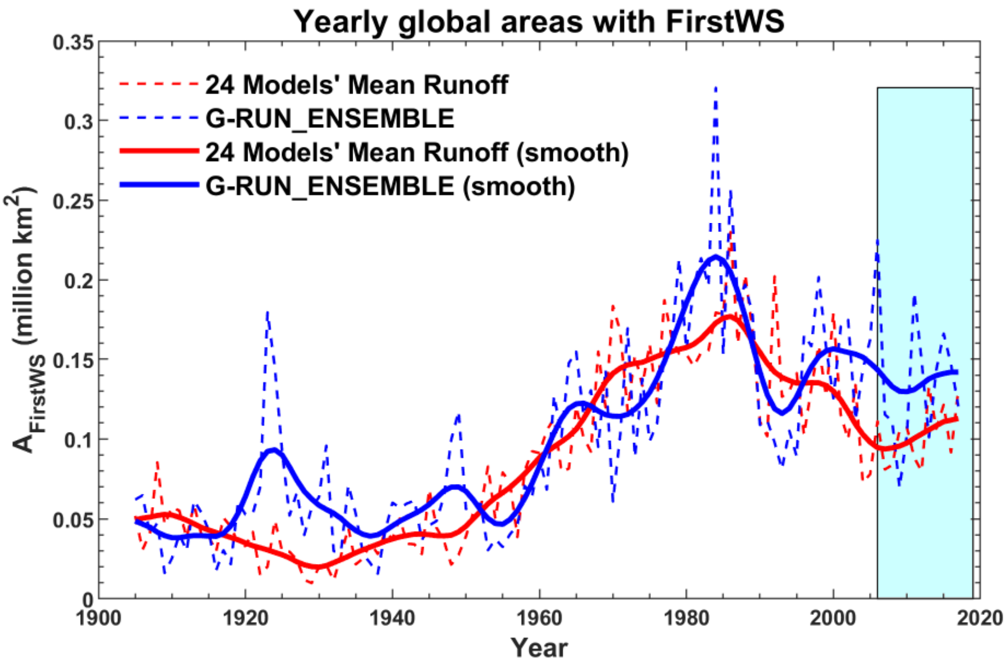
Supplementary Fig. 21. The spatial distributions of the first occurrence time for water shortages (FirstWS) with the threshold of 1000 m^3/person/yr, but the water availability per capita was produced using 5-year running-mean and 21-year running-mean. (a) historical (1901-2020) FirstWS with 5-year moving average; (b) future (2021-2090) FirstWS with 5-year moving average; (c) historical (1901-2020) FirstWS with 21-year moving average; (d) future (2021-2090) FirstWS with 21-year moving average; (e) the annual global area for a specific year when FirstWS is reached ($A_{FirstWS}$). Noted that here we only show RCP2.6-SSP2 scenario.



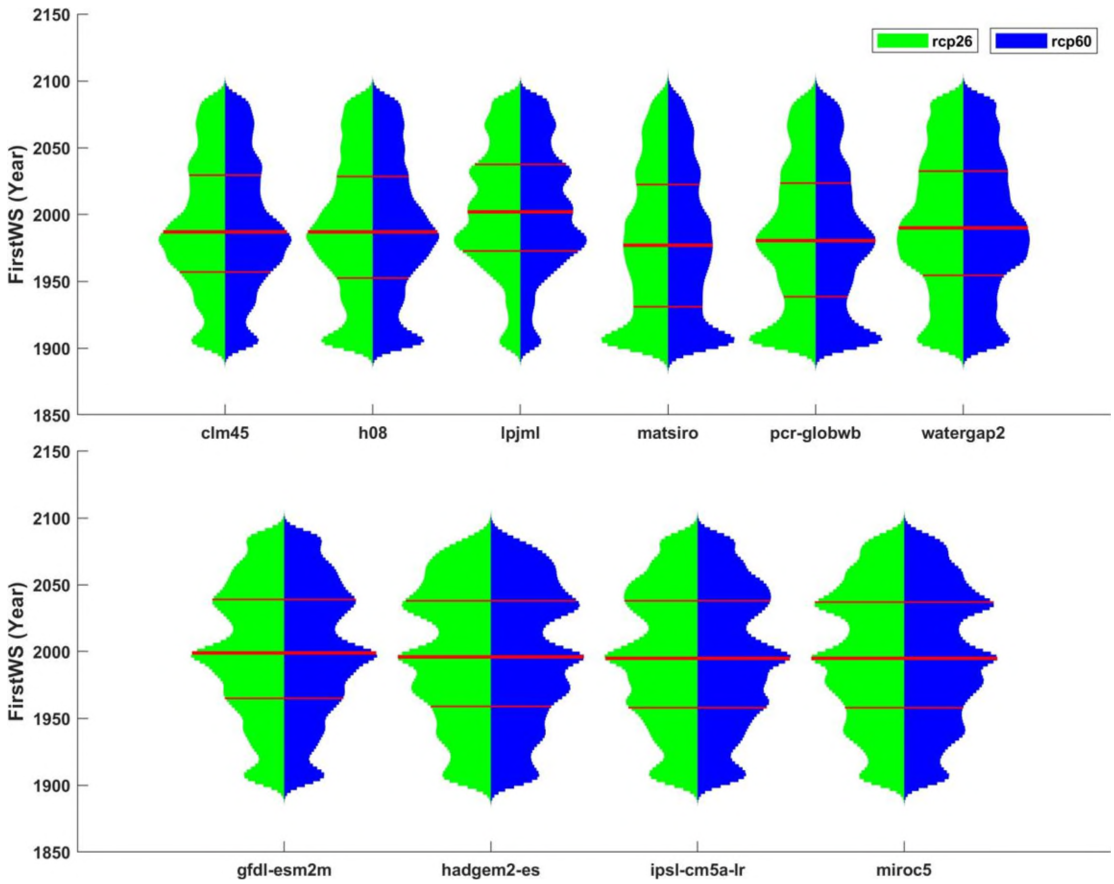
Supplementary Fig. 22. The trends of the first occurrence time for water shortages (FirstWS) with the threshold of 500, 1000 and 1700 m^3/person/yr. (a) the annual global area for a specific year when FirstWS is reached ($A_{FirstWS}$) for the RCP2.6-SSP2 scenario. (b)) the annual global area for a specific year when FirstWS is reached ($A_{FirstWS}$) for the RCP6.0-SSP2.



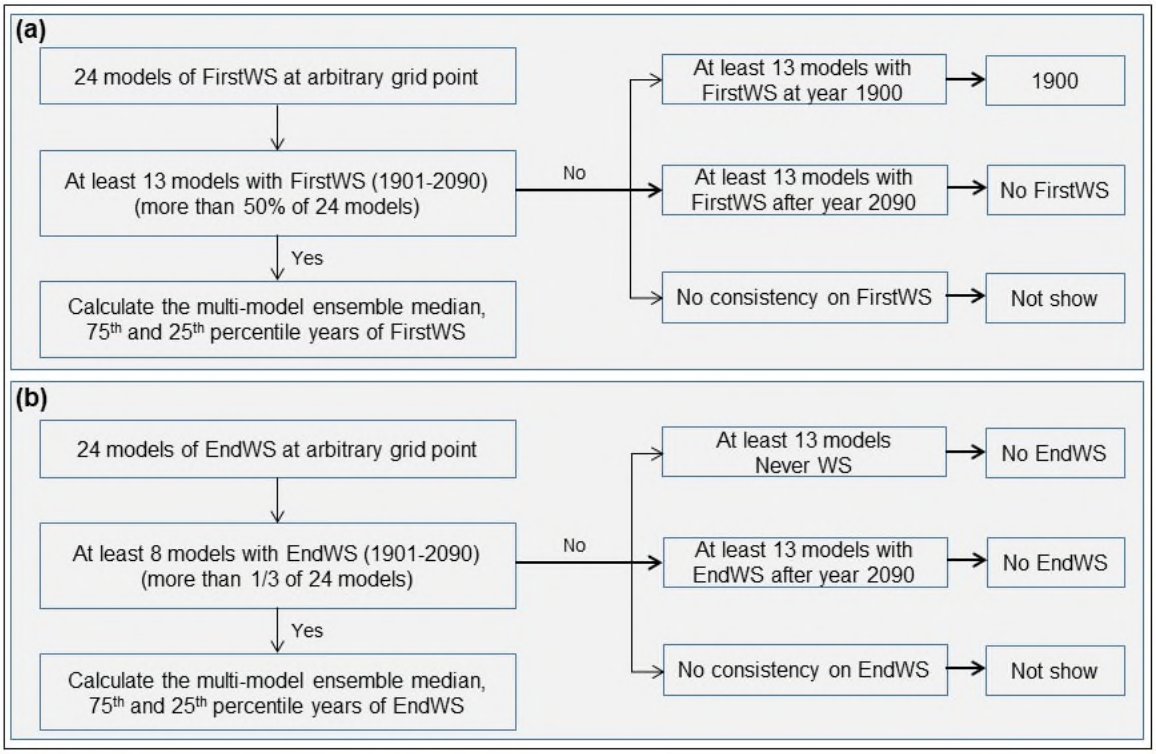
Supplementary Fig. 23. The spatial distributions of the first occurrence time for water scarcity (FirstWS) on watershed scale. The map is the same as **Figure 2** in the main text, but the difference is that the FirstWS was calculated at watershed scale. (a) Historical periods (1901-2020); (b) future periods (2021-2090) under RCP2.6-SSP2 combination; (c) future periods under RCP6.0-SSP3 combination; (d) The comparison of annual global area of FirstWS ($A_{FirstWS}$) between grid-scale results and watershed-scale results. In (a), the gray color indicates that water scarcity occurred before 1901 and the white color indicates that water scarcity has never occurred in the historical period. In (b) and (c), the gray color means that water scarcity occurs before 2021. The white color indicates that water scarcity never occurs before 2090. This map was produced with the threshold of 1000 m^3/person/yr and smoothed with 11-year running window.



Supplementary Figure 24. The comparison of $A_{FirstWS}$ between G-RUN and our models of FirstWS in historical periods (1901-2020). Noted that the models' runoff data only ranges from 1901 to 2005 in historical periods. The year between 2006 and 2020 is from the runoff in RCP2.6 scenario. The runoff of G-RUN ensemble ranges from 1902 to 2019.



Supplementary Fig. 25. The impacts of four General Circulation Models (GCMs)and six Global Hydrological Models (GHMs) on the estimated FirstWS. (a) the comparison of FirstWS among six GHMs; (b) the comparison of FirstWS among four GCMs. The green color represents RCP 2.6 while blue color represents RCP 6.0. The red line denotes the 25, 50, 75 percentiles. The violin plots reflect on the distribution of FirstWS from 1901 to 2090.



Supplementary Fig. 26. The flow chart to calculate the multi-model ensemble median, 25th and 75th percentile years of (a) FirstWS and (b) EndWS.

Supplementary Tables

Supplementary Table 1. Summary of multi-model ensemble simulations of total runoff. 'Y' denotes there is runoff data. Noted that CLM4.5 does not provide *total runoff* with time-varying historical socio-economic scenarios, but only with socio-economic scenarios fixed at 2005 level.

	Climate scenarios	**Historical**		**RCP2.6**		**RCP6.0**	
	Simulation Period	**1861-2005**		**2006-2099**		**2006-2099**	
GHM/LSM	**Socio-economic Scenarios / GCM**	**Histsoc**	**2005soc**	**2005soc**	**rcp26soc**	**2005soc**	**rcp60soc**
CLM 4.5	GFDL-ESM2M		Y	Y		Y	
	HADGEM2-ES		Y	Y		Y	
	IPSL-CM5A-LR		Y	Y		Y	
	MIROC5		Y	Y		Y	
H08	GFDL-ESM2M	Y		Y	Y	Y	Y
	HADGEM2-ES	Y		Y	Y	Y	Y
	IPSL-CM5A-LR	Y		Y	Y	Y	Y
	MIROC5	Y		Y	Y	Y	Y
LPJ-mL	GFDL-ESM2M	Y		Y	Y	Y	Y
	HADGEM2-ES	Y		Y	Y	Y	Y
	IPSL-CM5A-LR	Y		Y	Y	Y	Y
	MIROC5	Y		Y	Y	Y	Y
PCR- GLOBWB	GFDL-ESM2M	Y		Y		Y	
	HADGEM2-ES	Y		Y		Y	
	IPSL-CM5A-LR	Y		Y		Y	
	MIROC5	Y		Y		Y	
WaterGAP2	GFDL-ESM2M	Y		Y		Y	
	HADGEM2-ES	Y		Y		Y	
	IPSL-CM5A-LR	Y		Y		Y	
	MIROC5	Y		Y		Y	
MATSIRO	GFDL-ESM2M	Y		Y	Y	Y	Y
	HADGEM2-ES	Y		Y	Y	Y	Y
	IPSL-CM5A-LR	Y		Y	Y	Y	Y
	MIROC5	Y		Y	Y	Y	Y

Histsoc: time-varying, historical socio-economic scenarios.

2005soc: socio-economic scenarios fixed at 2005 level.

rcp26soc (rcp60soc): Varying water abstraction and land use according to SSP2 and RCP2.6 (RCP60); fixed year-2005 dams and reservoirs.

Supplementary Table 2. Number of pixels and terrestrial area for the four patterns synthesized in Fig. 1. The values show the mean of the ensembles ± standard deviation of the simulations from 24 Global Hydrological Models (GHMs) - General Circulation Models (GCMs) simulations under RCP2.6-SSP2 combination for the period 1901-2090.

	Number of pixels	Terrestrial Area (million km^2)	Proportion of terrestrial area (%)
Never WS	32450±2893	79±7	53±5
Always WS	2383±2053	6±5	4±3
Intermittent WS Type I	6658±1253	18±3	12±2
Intermittent WS Type II	2862± 826	7±2	5±1

Supplementary Table 3. The cumulative areas crossed FirstWS aggregated over the six continental regions in historical (1901-2020) and future period (2021-2090). Historical period is from 1901 to 2020. For future scenarios, climate scenarios are RCP2.6 and RCP6.0, and population scenarios are SSP2 and SSP3. The value is the mean of 24 Global Hydrological Models (GHMs) - General Circulation Models (GCMs) ensembles and 1± standard deviation of 24 models ensembles. The unit is million km^2.

	Historical	RCP2.6-SSP2	RCP6.0-SSP2	RCP2.6-SSP3	RCP6.0-SSP3
Africa	4.05±0.97	2.50±0.41	2.50±0.55	3.32±0.49	3.27±0.60
Asia	5.64±1.18	1.24±0.23	1.36±0.42	1.77±0.30	1.84±0.46
Oceania	0.13±0.09	0.09±0.07	0.09±0.07	0.05±0.05	0.05±0.05
North America	1.14±0.37	0.32±0.11	0.41±0.17	0.32±0.11	0.38±0.16
South America	0.63±0.17	0.20±0.08	0.20±0.08	0.34±0.10	0.35±0.11
Europe	0.74±0.19	0.15±0.07	0.19±0.07	0.09±0.06	0.10±0.05

Supplementary Table 4. The top ten countries with the largest $A_{FirstWS}$ between 1901 and 2090. The value is the mean of 24 Global Hydrological Models (GHMs) - General Circulation Models (GCMs) ensembles and 1 ± standard deviation of 24 models ensembles. The unit is million km^2.

RCP2.6-SSP2		RCP6.0-SSP2		RCP2.6-SSP3		RCP6.0-SSP3	
China	1.69±0.33	CHINA	1.71±0.33	China	1.70±0.36	CHINA	1.72±0.37
India	1.43±0.31	INDIA	1.62±0.33	India	1.40±0.32	INDIA	1.53±0.33
USA	0.75±0.24	SUDAN	0.80±0.23	USA	0.81±0.25	SUDAN	0.80±0.24
Sudan	0.73±0.23	USA	0.64±0.23	Sudan	0.73±0.24	USA	0.67±0.24
Iran	0.49±0.23	NIGERIA	0.59±0.08	Iran	0.52±0.26	MEXICO	0.60±0.22
Mexico	0.48±0.18	MEXICO	0.56±0.19	Mexico	0.51±0.20	NIGERIA	0.60±0.09
Nigeria	0.48±0.09	IRAN	0.53±0.24	Nigeria	0.49±0.11	IRAN	0.57±0.26
South Africa	0.47±0.20	PAKISTAN	0.50±0.17	Algeria	0.48±0.20	ALGERIA	0.51±0.20
Ethiopia	0.47±0.14	SOUTH AFRICA	0.47±0.20	South Africa	0.47±0.20	PAKISTAN	0.50±0.17
Pakistan	0.45±0.16	ETHIOPIA	0.47±0.14	Pakistan	0.46±0.16	NIGER	0.48±0.15

Supplementary Table 5. The cumulative areas crossed FirstWS aggregated over the top ten populous countries in historical (1901-2020) and future period (2021-2090). Historical period is from 1901 to 2020. For future scenarios, climate scenarios are RCP2.6 and RCP6.0, and population scenarios are SSP2 and SSP3. The value is the mean of 24 models ensembles and 1± standard deviation of 24 models ensembles. The unit is million km^2.

	Historical	RCP2.6-SSP2	RCP6.0-SSP2	RCP2.6-SSP3	RCP6.0-SSP3
China	1.65±0.31	0.07±0.04	0.08±0.05	0.09±0.04	0.11±0.06
India	1.18±0.26	0.30±0.11	0.25±0.17	0.50±0.16	0.38±0.21
USA	0.59±0.21	0.18±0.06	0.24±0.07	0.08±0.05	0.11±0.05
Sudan	0.51±0.14	0.21±0.08	0.21±0.10	0.29±0.09	0.28±0.11
Iran	0.45±0.22	0.08±0.04	0.13±0.09	0.13±0.06	0.19±0.10
Mexico	0.38±0.13	0.10±0.08	0.12±0.08	0.18±0.09	0.20±0.10
Nigeria	0.19±0.08	0.35±0.07	0.36±0.10	0.47±0.09	0.47±0.11
South Africa	0.42±0.19	0.10±0.06	0.12±0.06	0.10±0.06	0.13±0.06
Ethiopia	0.32±0.13	0.22±0.08	0.18±0.09	0.23±0.09	0.19±0.10
Pakistan	0.36±0.15	0.12±0.07	0.12±0.07	0.17±0.10	0.16±0.10

Supplementary Table 6. The cumulative areas crossed EndWS aggregated over the six continental regions in historical (1901-2020) and future period (2021-2090). Historical period is from 1901 to 2020. For future scenarios, climate scenarios are RCP2.6 and RCP6.0, and population scenarios are SSP2 and SSP3. The value is the mean of 24 Global Hydrological Models (GHMs) - General Circulation Models (GCMs) ensembles and 1± standard deviation of 24 models ensembles. The unit is million km^2.

	Historical	RCP2.6-SSP2	RCP6.0-SSP2	RCP2.6-SSP3	RCP6.0-SSP3
Africa	0.06±0.05	0.90±0.46	1.14±0.47	0.73±0.40	0.95±0.42
Asia	0.24±0.11	2.05±0.57	2.17±0.41	1.49±0.52	1.56±0.38
Oceania	0.01±0.01	0.07±0.09	0.08±0.09	0.08±0.08	0.08±0.09
North America	0.04±0.06	0.29±0.15	0.24±0.11	0.35±0.16	0.29±0.13
South America	0.02±0.01	0.25±0.10	0.23±0.09	0.21±0.10	0.20±0.10
Europe	0.09±0.06	0.35±0.14	0.26±0.12	0.42±0.13	0.33±0.13

Supplementary Table 7. The top ten countries with the largest A_{EndWS} between 1901 and 2090. The value is the mean of 24 Global Hydrological Models (GHMs) - General Circulation Models (GCMs) ensembles and 1 ± standard deviation of 24 models ensembles. The unit is million km^2.

RCP2.6-SSP2		RCP6.0-SSP2		RCP2.6-SSP3		RCP6.0-SSP3	
China	1.01±0.20	CHINA	0.75±0.19	China	1.05±0.21	CHINA	0.80±0.20
India	0.29±0.15	UNITED STATES	0.26±0.13	India	0.52±0.19	INDIA	0.30±0.15
Iran	0.22±0.17	IRAN	0.19±0.16	Sudan	0.23±0.19	USA	0.22±0.12
Russian	0.18±0.12	RUSSIAN	0.15±0.11	Russian	0.18±0.12	SUDAN	0.19±0.17
USA	0.18±0.10	INDIA	0.14±0.09	USA	0.15±0.10	RUSSIAN	0.16±0.12
Sudan	0.14±0.11	AUSTRALIA	0.12±0.17	Saudi Arabia	0.15±0.11	SAUDI ARABIA	0.13±0.11
Algeria	0.14±0.15	SAUDI ARABIA	0.12±0.09	Iran	0.12±0.11	AUSTRALIA	0.13±0.17
Saudi Arabia	0.13±0.10	ALGERIA	0.11±0.14	Australia	0.12±0.17	ETHIOPIA	0.11±0.11
Brazil	0.13±0.07	BRAZIL	0.11±0.06	Ethiopia	0.11±0.11	LIBYA	0.10±0.09
Mexico	0.12±0.06	SUDAN	0.10±0.09	Algeria	0.10±0.08	IRAN	0.09±0.10

Supplementary Table 8. The cumulative areas crossed EndWS aggregated over the top ten populous countries in historical (1901-2020) and future period (2021-2090). Historical period is from 1901 to 2020. For future scenarios, climate scenarios are RCP2.6 and RCP6.0, and population scenarios are SSP2 and SSP3. The value is the mean of Global Hydrological Models (GHMs) - General Circulation Models (GCMs) models ensembles and 1± standard deviation of 24 models ensembles. The unit is million km^2.

	Historical	RCP2.6-SSP2	RCP6.0-SSP2	RCP2.6-SSP3	RCP6.0-SSP3
China	0.13±0.04	0.87±0.20	0.91±0.19	0.63±0.19	0.67±0.18
India	0.01±0.01	0.26±0.13	0.51±0.18	0.12±0.09	0.29±0.15
USA	0.04±0.05	0.14±0.08	0.11±0.07	0.21±0.09	0.18±0.08
Sudan	0.01±0.01	0.11±0.08	0.18±0.14	0.08±0.07	0.14±0.11
Iran	0.01±0.01	0.21±0.17	0.12±0.11	0.18±0.16	0.08±0.10
Mexico	0.01±0.01	0.11±0.06	0.08±0.05	0.09±0.05	0.06±0.04
Nigeria	0.00±0.00	0.01±0.01	0.01±0.01	0.01±0.01	0.01±0.01
South Africa	0.00±0.01	0.05±0.05	0.05±0.05	0.05±0.05	0.05±0.05
Ethiopia	0.01±0.02	0.06±0.07	0.13±0.12	0.06±0.06	0.12±0.12
Pakistan	0.00±0.00	0.04±0.02	0.06±0.03	0.03±0.02	0.04±0.03

Supplementary Table 9. The cumulative people crossed FirstWS aggregated over the six continental regions in historical (1901-2020) and future period (2021-2090). The unit is million persons. Historical period is from 1901 to 2020. For future scenarios, climate scenarios are RCP2.6 and RCP6.0, and population scenarios are SSP2 and SSP3. The value is the mean of 24 Global Hydrological Models (GHMs) - General Circulation Models (GCMs) ensembles and 1± standard deviation of 24 models ensembles.

	Historical	RCP2.6-SSP2	RCP6.0-SSP2	RCP2.6-SSP3	RCP6.0-SSP3
Africa	196.29± 24.67	388.55±50.09	370.78±45.39	573.87± 75.46	554.83± 61.71
Asia	964.05±110.54	297.11±58.91	280.28±98.59	517.62±111.34	454.13±143.12
Oceania	5.93± 1.71	3.55± 1.14	3.40± 1.45	1.68± 0.99	1.23± 0.84
North America	97.24± 10.42	46.08± 7.43	56.60±15.59	44.76± 5.50	48.34± 8.87
South America	61.22±5.67	22.80± 6.87	20.22± 5.70	36.32± 8.18	37.17± 8.70
Europe	115.80± 15.87	24.68± 5.78	31.12± 4.92	11.65± 4.21	12.38± 3.46

Supplementary Table 10. The cumulative people crossed FirstWS aggregated over the top ten populous countries in historical (1901-2020) and future period (2021-2090). The unit is million persons. Historical period is from 1901 to 2020. For future scenarios, climate scenarios are RCP2.6 and RCP6.0, and population scenarios are SSP2 and SSP3. The value is the mean of 24 Global Hydrological Models (GHMs) - General Circulation Models (GCMs) ensembles and 1± standard deviation of 24 models ensembles.

	Historical	RCP2.6-SSP2	RCP6.0-SSP2	RCP2.6-SSP3	RCP6.0-SSP3
China	321.54±44.61	13.44± 8.51	16.15± 8.38	18.07±11.01	21.74± 9.11
India	345.61±62.53	155.97±51.38	133.08±76.44	298.23±86.90	230.58±112.21
USA	57.32± 5.17	32.02± 8.33	38.61±11.52	9.49± 4.48	10.52± 4.43
Sudan	7.13± 1.82	8.76± 3.71	8.52± 4.26	14.45± 6.01	13.43± 6.69
Iran	14.15± 5.72	5.01± 2.44	8.12± 4.68	9.38± 3.71	13.39± 6.67
Mexico	18.89± 3.77	7.62± 5.40	9.52± 4.90	17.22± 5.04	19.34± 5.64
Nigeria	39.03± 6.96	140.25±24.56	144.57±28.31	205.57±37.26	210.44± 36.11
South Africa	11.15± 2.43	4.41± 1.55	4.73± 1.66	5.05± 1.74	5.26± 1.76
Ethiopia	20.07± 7.25	39.91±14.47	34.04±17.00	48.06±17.21	40.77± 21.07
Pakistan	40.76±20.26	19.60±17.26	19.35±16.85	31.51±28.37	30.28± 27.62

Supplementary Table 11. The cumulative people crossed EndWS aggregated over the six continental regions top ten populous countries in historical (1901-2020) and future period (2021-2090). The unit is billion persons. Historical period is from 1901 to 2020. For future scenarios, climate scenarios are RCP2.6 and RCP6.0, and population scenarios are SSP2 and SSP3. The value is the mean of 24 Global Hydrological Models (GHMs) - General Circulation Models (GCMs) ensembles and 1± standard deviation of 24 models ensembles.

	Historical	RCP2.6-SSP2	RCP6.0-SSP2	RCP2.6-SSP3	RCP6.0-SSP3
Africa	0.33±0.39	46.52±17.33	71.62±28.26	42.68±18.31	70.77± 29.12
Asia	12.95±7.58	406.84±92.15	503.66±96.43	285.97±72.85	363.06±100.07
Oceania	0.01±0.02	0.79± 0.73	0.92± 0.74	1.41± 0.78	1.24± 0.61
North America	0.31±0.42	22.85± 7.68	20.67± 4.64	36.30±10.71	32.00± 7.00
South America	0.27±0.31	21.59± 7.96	22.41± 7.63	13.94± 4.66	13.83± 5.64
Europe	8.26±3.85	44.24±10.82	33.50±10.13	64.93±10.93	51.08± 10.24

Supplementary Table 12. The cumulative people crossed EndWS aggregated over the top ten populous countries in historical (1901-2020) and future period (2021-2090). The unit is billion persons. Historical period is from 1901 to 2020. For future scenarios, climate scenarios are RCP2.6 and RCP6.0, and population scenarios are SSP2 and SSP3. The value is the mean of 24 Global Hydrological Models (GHMs) - General Circulation Models (GCMs) ensembles and 1± standard deviation of 24 models ensembles.

	Historical	RCP2.6-SSP2	RCP6.0-SSP2	RCP2.6-SSP3	RCP6.0-SSP3
China	8.08±6.63	181.32±49.86	169.69±46.12	133.29±44.36	124.20±35.68
India	1.09±1.65	116.45±51.50	225.68±83.88	62.07±41.88	149.60±80.28
USA	0.08±0.12	10.68± 4.21	8.04± 4.19	22.97± 5.77	16.98± 3.91
Sudan	0.06±0.10	3.46± 3.32	4.83± 4.64	3.43± 3.63	4.42± 4.63
Iran	0.05±0.09	8.53± 6.57	4.86± 3.65	8.57± 7.41	3.52± 4.82
Mexico	0.05±0.10	5.85± 3.03	3.35± 1.93	5.44± 3.20	3.50± 1.97
Nigeria	0.00±0.00	3.12± 3.46	3.33± 3.81	2.44± 4.51	1.87± 2.12
South Africa	0.03±0.08	1.41± 1.22	1.14± 1.04	1.72± 1.51	1.26± 1.25
Ethiopia	0.08±0.21	4.74± 3.87	13.16±14.69	6.41± 5.30	17.93±20.06
Pakistan	0.03±0.08	3.58± 2.29	8.35± 4.66	2.95± 2.99	7.13± 5.40