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Current and future global water scarcity intensifies when accounting for surface water quality

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The inadequate availability of clean water presents systemic risks to human health, food production, energy generation and ecosystem functioning. Here we evaluate population exposure to current and future water scarcity (both excluding and including water quality) using a coupled global hydrological and surface water quality model. We find that 55% of the global population are currently exposed to clean water scarcity at least one month per year, compared with 47% considering water quantity aspects only. Exposure to clean water scarcity at least one month per year increases to 56–66% by the end of the century. Increases in future exposure are typically largest in developing countries—particularly in sub-Saharan Africa—driven by a combination of water quantity and quality aspects. Strong reductions in both anthropogenic water use and pollution are therefore necessary to minimize the impact of future clean water scarcity on humans and the environment.

Human activities, including crop and livestock production, manufacturing of goods, power generation and domestic activities, rely on the availability of water in both adequate quantities and of acceptable quality for the intended use[1,2]. However, geographic and temporal mismatches between clean water availability and demands occur across different world regions and at certain times[2,3]. The inability to meet our clean water demands, both now and in the future, is considered to be one of the major threats to humankind both in terms of likelihood and potential impacts—and is increasingly perceived as a global systemic risk[3]. Recognizing the importance of addressing this risk, the United Nations established Sustainable Development Goal (SDG) 6.4 to "substantially reduce the number of people suffering from water scarcity"[4].

Global water scarcity assessments have sought to identify areas susceptible to water scarcity issues with the aims of raising awareness, assessing the state and trends of sub-regional to global development targets and guiding regional- to national-scale policies and investments in adaptive solutions[5,6]. Although it is now widely recognized that water quality aspects should also be considered in water scarcity assessments, relatively few studies have sought to address this knowledge gap[5,7]. Those that do exist have consistently demonstrated that the impact of poor water quality on water scarcity is substantial[2,8–11]. For example, when multiple water quality constituents were included in an assessment of historical water scarcity (2000–2010), the global population exposed to severe water scarcity issues increased from 30% (22–35% monthly range) to 40% (31–46%)[2].

Existing assessments of future water scarcity have shown that increases in global water demands associated with population growth, economic development and dietary shifts[12–14], coupled with changes in water availability due to altered hydrometeorological regimes[15], will exacerbate water scarcity issues globally[3,16–18]. However, these assessments have largely overlooked the role of (changing) water quality. In this study we estimate population exposure to water scarcity until the end of the century, accounting for multiple pollutants, sector-specific water quality requirements and seasonality.

To this end, we use simulations from a state-of-the-art global hydrological and water resources model (PCR-GLOBWB 2) (for example, discharge, groundwater abstraction and water demand) coupled with a multi-pollutant surface water quality model (DynQual) (salinity, organic pollution and pathogen pollution) for the time period 2005–2100. We identify water scarcity hotspots and estimate the number

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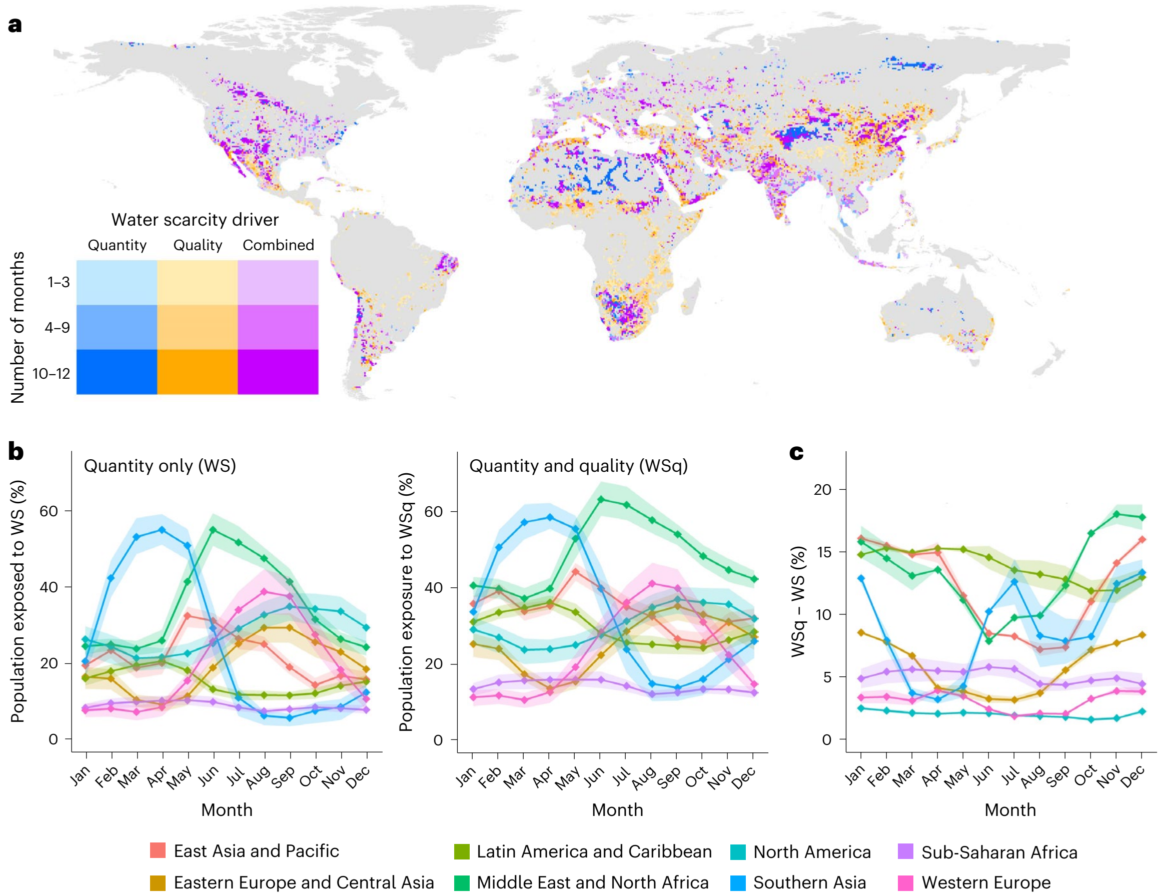

Fig. 1 | Spatial distribution, seasonal patterns and drivers of current hotspots of and population exposure to water scarcity. a, Water scarcity hotspots and their drivers. Quantity indicates water quantity aspects alone drive water scarcity (that is, insufficient water availability, no water quality issues). Quality indicates water quality aspects alone drive water scarcity (that is, sufficient water availability, exceedance of water quality thresholds). Combined indicates that both are quantity and quality aspects drive water scarcity (that is, insufficient water availability, exceedance of water quality thresholds). Hotspots are colour coded to show the number of months that the given conditions exist per year averaged over a historical reference period (2005–2020). **b**, The percentage of the global population exposed to water scarcity per month based on WS (left) and WSq (right) averaged over the historical reference period. **c**, The exacerbation of water scarcity due to water quality aspects alone (that is, the difference between WSq and WS). The coloured lines show the mean average exposure over the entire reference period and the shaded envelopes mark the 25th and 75th percentile values for individual years within the reference period. Map shapefile in **a** from The World Bank under a Creative Commons license CC BY 4.0.

of people exposed globally for both present-day conditions and until the end of the century under (uncertain) trajectories of climate and societal change. Given fundamental uncertainties in trajectories of climate change and socio-economic development, exploring different possible futures is an essential part of global change assessments[19]. To achieve this, we consider three combinations of Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) with five global climate models (GCMs) to better account for uncertainties inherent in the future projections.

Present-day water scarcity

The driver of water scarcity—be that water quantity (that is, insufficient water availability, no quality issues), water quality (that is, sufficient water availability, exceedance of water quality thresholds) or a combination of both of these aspects (that is, insufficient water availability, exceedance of water quality thresholds)—varies in both space and time (Fig. 1a). However, with surface water quality issues ubiquitous across the globe at present[2,20–22], the inclusion of water quality exacerbates water scarcity in areas of all world regions for at least part of the year. For example, seasonal exceedances of water quality thresholds induce conditions of water scarcity in east Africa and large parts of China, often despite sufficient water availability. India suffers from the combined impacts of insufficient water availability and quality in many areas for large parts of the year. The most populated regions of Western Europe and North America also experience water scarcity, most commonly in the summer months, driven predominantly by water quantity issues but often further exacerbated by poor water quality.

Population exposure to water scarcity due to water quantity alone (WS) and water scarcity including water quality (WSq) varies drastically across the year and geographic regions (Fig. 1b). Globally, the current monthly range in exposure to water scarcity is between 15% (1.0 billion people) and 30% (2.1 billion people) as quantified by WS, and increases to between 24% (1.7 billion people) and 37% (2.6 billion people) when quantified by WSq. The impact of including water quality has the strongest effect on the number of people exposed to water scarcity in the Latin America and Caribbean, Middle East and North Africa, and East Asia and Pacific regions.

Our results also suggest that 3.8 billion people (55%) are now exposed to WSq at least one month per year, with 1.1 billion people (16%) exposed for more than nine months per year (Table 1 and Fig. 2). Proportionately, the impact of water quality on water scarcity and the difference between population exposure to WS and WSq increases when multi-seasonal to year-round exceedances are considered. For example, an estimated 0.71 billion people (10.3%) face WSq in every month of the year, more than double that of the exposure to WS (4.6%; 0.32 billion people) (Table 1). Conversely, when considering exposure

Table 1 | Present-day population exposure to water scarcity

Number of months per year (*n*)	Exposure to water scarcity in at least *n* months (2005–2020)			
	WS (%)	WS (billion)	WSq (%)	WSq (billion)
0	100	6.90	100	6.90
1	47.3	3.26	55.4	3.82
2	42.4	2.93	50.9	3.52
3	37.3	2.58	46.3	3.19
4	31.7	2.19	41.4	2.86
5	24.5	1.69	35.6	2.46
6	17.7	1.22	29.6	2.04
7	14.0	0.97	25.4	1.75
8	11.4	0.79	21.8	1.51
9	9.4	0.65	18.7	1.29
10	7.7	0.53	15.8	1.09
11	6.1	0.42	13.0	0.90
12	4.6	0.32	10.3	0.71

The percentage of the global population and the number of people who face water scarcity issues are averaged over 2005–2020.

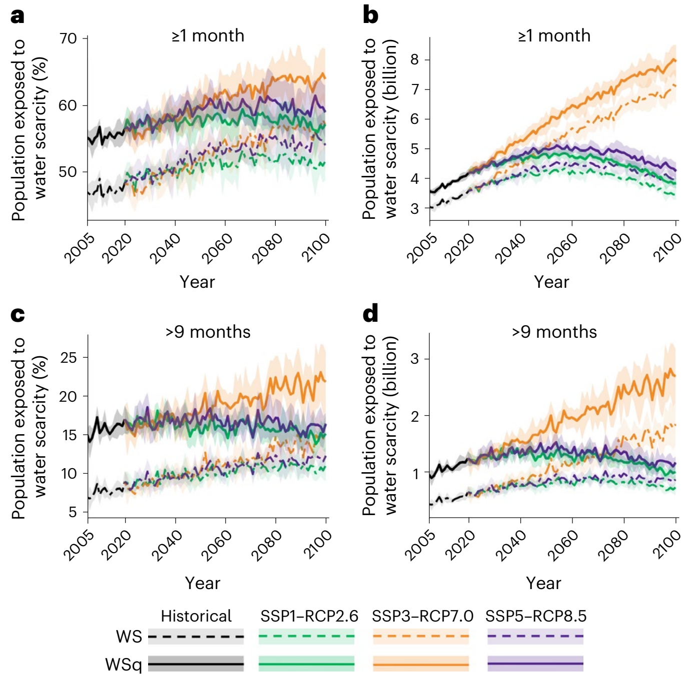

Fig. 2 | Global population exposure to water scarcity under uncertain climate and socio-economic change. a,**c**, Percentage of the global population exposed to water scarcity for at least one month per year (**a**) and for more than 9 months per year (**c**) from 2005–2100 based on WS and WSq indicators. **b**,**d**, The corresponding total number of people exposed to water scarcity. Lines show the mean average exposure per year averaged over the five GCMs considered and the shaded envelopes represent the uncertainty arising from variations in GCM simulations (±1 s.d.). Individual percentage exposure plots for all world regions are shown in Extended Data Figs. 1–8.

to WS and WSq for at least 1 month per year, the difference is around one-fifth (WS: 3.3 billion; WSq: 3.8 billion). This suggests that, in some world regions, mismatches between in-stream concentrations and sectoral quality requirements persist for a greater proportion of the year compared with the mismatches between water demands and availability.

Future water scarcity

Population exposure to clean water scarcity in the future is dependent on trajectories of water demand, availability and quality, which are influenced by a combination of climate and socio-economic change.

Under all three combinations of socio-economic and climate scenarios considered, both the proportion and number of people exposed to water scarcity for at least one month per year increased (Fig. 2a,b, Table 2 and Extended Data Table 1). Similar patterns were observed for exposure to water scarcity for >9 months per year (Fig. 2c,d and Supplementary Tables 3–4). Across the three scenarios, differences in the exposure to water scarcity as a proportion of people began to noticeably diverge after the year 2050, whereas the total number of people exposed (which is sensitive to different scenarios of population growth) diverged around 2030. Globally, across the three scenarios and five GCMs, an average of 56–62% of people were exposed to clean water scarcity (WSq) one month per year by mid-century (2041–2060), which became 56–66% by the end of the century (2081–2100), compared with 54–57% in the historic reference period (2005–2020) (Table 2). This translated into an increase from 3.8–3.9 billion people at present to between 4.7–6.1 billion and 3.8–8.2 billion people by mid-century and the end of the century, respectively. Globally, the population exposed to water scarcity, assessed both proportionally and by the total number of people, was highest under SSP3–RCP7.0, followed by SSP5–RCP8.5 and then SSP1–RCP2.6 (Figs. 2 and 3).

Exposure to water scarcity at monthly resolution from 2005–2100 under the three scenarios further highlights the inter- and intra-annual components of current and future global water scarcity (Fig. 3a and Extended Data Figs. 1–8). Monthly exposure to WSq was projected to range between 2.1–3.2, 2.7–4.1 and 2.3–3.4 billion people by mid-century and 1.9–2.7, 3.6–5.5 and 2.1–2.9 billion people by the end of the century under SSP1–RCP2.6, SSP3–RCP7.0 and SSP5–RCP8.5, respectively. Inadequate water quality was responsible for an average monthly increase in exposure to WSq of 585, 839 and 630 million people by mid-century, and 397, 955 and 393 million people by the end of the century under SSP1–RCP2.6, SSP3–RCP7.0 and SSP5–RCP8.5, respectively, compared with WS. Plots displaying monthly exposure to water scarcity for mid-century and the end of the century with respect to the current seasonal patterns also highlight changes to future (seasonal) patterns in global water scarcity under the different climate and socio-economic scenarios (Fig. 3b). Exacerbation of WS indicates more frequent and widespread water quantity gaps (that is, instances where human water demands exceed the renewable water supply), whereas increases in WSq are also reflective of changes to exceedances of critical water quality thresholds. Population exposure to water scarcity is highest under SSP3–RCP7.0 for almost all months, particularly at the end of the century.

Global aggregations mask strong (and seasonal) differences in future water scarcity across different world regions (Fig. 4, Table 2, Extended Data Table 1, Extended Data Figs. 1–8 and Supplementary Tables 1–4). Water scarcity (WS and WSq) increases in almost all world regions, except in the East Asia and Pacific region where substantial decreases in the proportion (Fig. 4) and the number of people (Extended Data Fig. 1) exposed to water scarcity are projected under all three scenarios. Long-term trends of exposure to water scarcity for different frequencies (>1 month, >9 months) show distinct decreases in population exposure throughout the year for WSq, but this is less prevalent for WS (Table 2 and Extended Data Fig. 1). As such, the overall decrease in population exposure to water scarcity in East Asia and Pacific is predominantly driven by improvements in surface water quality.

Water scarcity in the Eastern Europe & Central Asia region is exacerbated under SSP3–RCP7.0 and SSP5–RCP8.5, and is also strongly seasonal (July–September), whereas under SSP1–RCP2.6 there is a

Table 2 | Future population exposure to clean water scarcity

Region	Population exposure to WSq at least 1 month per year (%)						
	Historical	2041–2060			2081–2100		
		SSP1–RCP2.6	SSP3–RCP7.0	SSP5–RCP8.5	SSP1–RCP2.6	SSP3–RCP7.0	SSP5–RCP8.5
Global	55.4	57.8	60.0	59.6	57.4	63.8	59.6
	(54.4–56.5)	(56.3–59.5)	(57.7–62.3)	(58.1–61.3)	(56.0–59.0)	(61.4–66.3)	(56.6–62.3)
East Asia and Pacific	61.7	60.2	61.3	61.7	57.9	61.3	60.2
	(59.2–63.4)	(58.3–62.4)	(59.7–63.1)	(59.3–64.3)	(55.8–60.0)	(59.0–63.4)	(58.0–62.1)
Eastern Europe and Central Asia	45.4	47.6	51.9	51.0	45.2	59.7	56.1
	(41.3–48.4)	(44.4–50.8)	(49.1–54.9)	(45.7–55.2)	(42.2–48.1)	(55.8–63.0)	(50.4–61.8)
Latin America and Caribbean	48.3	45.5	52.1	50.3	39.6	57.6	47.6
	(45.9–50.5)	(43.1–47.3)	(49.9–54.1)	(48.4–52.2)	(37.9–40.9)	(55.7–59.0)	(44.6–51.4)
Middle East and North Africa	72.9	76.2	82.0	77.7	79.2	85.1	77.4
	(68.2–77.7)	(72.4–82.1)	(78.5–86.9)	(73.0–83.3)	(76.0–84.0)	(80.7–89.8)	(72.3–84.1)
North America	48.4	55.3	52.7	58.4	59.5	49.5	66.0
	(45.0–53.0)	(50.9–59.6)	(48.6–57.7)	(54.3–62.4)	(55.6–64.0)	(44.1–54.4)	(61.4–70.2)
Southern Asia	66.9	70.3	71.9	72.3	69.7	73.5	67.8
	(63.9–70.6)	(66.7–73.7)	(76.7–76.1)	(69.5–76.0)	(67.3–73.8)	(66.9–79.6)	(63.5–72.5)
Sub-Saharan Africa	26.3	40.2	43.1	39.7	46.3	53.7	43.6
	(23.6–28.4)	(37.1–43.8)	(38.4–47.6)	(35.4–43.5)	(42.0–50.0)	(49.6–58.8)	(35.2–53.2)
Western Europe	50.0	56.9	53.5	59.6	54.5	54.6	67.5
	(45.5–55.4)	(52.2–61.6)	(48.7–58.9)	(55.0–63.9)	(49.6–59.6)	(48.1–62.4)	(63.4–71.5)

Values in parentheses indicate the variability in exposure to water scarcity across individual years within the aggregated time periods, combined with uncertainties in GCM simulations, as the 25th and 75th percentile values. The corresponding data for WS are displayed in Extended Data Table 1; tables for exposure to WS and WSq for >3 months per year are available as Supplementary Tables 1 and 2 and for >9 months per year as Supplementary Tables 3 and 4.

decrease in water scarcity for most months (Fig. 4 and Extended Data Fig. 2). Conversely, in North America (Extended Data Fig. 5) and Western Europe (Extended Data Fig. 8), increases in exposure to water scarcity are strongest under SSP5–RCP8.5 and SSP1–RCP2.6, predominantly driven by water quantity issues (that is, demand versus availability), with impacts strongest during the summer months (July–October) (Fig. 4). It should be noted that the projections of population change in North America and Western Europe are unique to these world regions, with strong growth under SSP5–RCP8.5 (North America +121%; Western Europe: +60%), more moderate growth under SSP1–RCP2.6 (North America: +45%; Western Europe: +8%) but negative growth under SSP3–RCP7.0 (North America: −18%; Western Europe: −37%) by 2100. Therefore, despite the strong increases in water use efficiencies achieved under SSP1–RCP2.6 and SSP5–RCP8.5, water demands are substantially higher in these scenarios than under SSP3–RCP7.0. In sub-Saharan Africa, strong increases in both the total number and proportion of people facing water scarcity (WS and WSq) are projected throughout the twenty-first century under all scenarios (Extended Data Fig. 7). While the total number of people in this region projected to face future water scarcity issues is strongly influenced by the population projections, substantial increases in the proportion of the population exposed to water scarcity across all months occur for both mid-century and the end of the century compared with current conditions (Table 2, Fig. 4 and Extended Data Fig. 7).

Discussion

While global hydrological models (GHMs) have been used to assess current and future water scarcity at high spatial (for example, 5 arcmin gridded) and temporal (for example, monthly) resolutions[17,18,23,24], these studies have overlooked the role of surface water quality. Leveraging a global surface water quality model, DynQual, we quantified future global water scarcity including both water quantity aspects and considering sectoral water quality requirements for multiple pollutants. The coupled hydrological and water quality modelling approach is advantageous for accounting for the relevant dependencies between water availability and quality, while the high spatiotemporal resolution of the model facilitates analysis of both intra- and intra-annual variability in water demands, availability and quality on water scarcity at a spatial resolution reflective of the scale at which water abstractions occur. These factors represent an advance from recent work[25], which focused on the impact of current and future nutrient pollution on surface water scarcity for aquatic ecosystems in global river basins.

Our results suggest that 3.8 billion people (55% of the global population) are now exposed to clean water scarcity (WSq) for at least one month per year, compared with 3.3 billion (47%) for WS. The current monthly range in exposure to WS is between 1.0 billion (15%) and 2.1 billion (30%), which increases to between 1.7 billion (24%) and 2.6 billion (37%) when also including water quality (*WSq*). Comparing estimates of WS and WSq suggests that, on average, an additional 634 (483–817 monthly range) million people are exposed to water scarcity due to a combination of salinity (total dissolved solids), organic (biological oxygen demand) and pathogen (faecal coliform) pollution.

Our estimates are on the high end of existing water scarcity assessments. For example, our results are similar to those obtained using the blue water footprint (~4 billion people)[3] and combined water shortage–water stress (3.8 billion people)[26] approaches, in addition to the 3.6 billion people (47%) estimated in *The United Nations World Water Development Report 2018*[27]. Our results therefore add weight to the argument that most previous studies have underestimated physical water scarcity—attributed to factors including coarse spatial (for example countries, river basins) and temporal (for example annual) resolutions, and a lack of consideration of water quality aspects. It should be noted that while it is widely accepted that water scarcity assessment should be conducted at monthly, instead of annual, time

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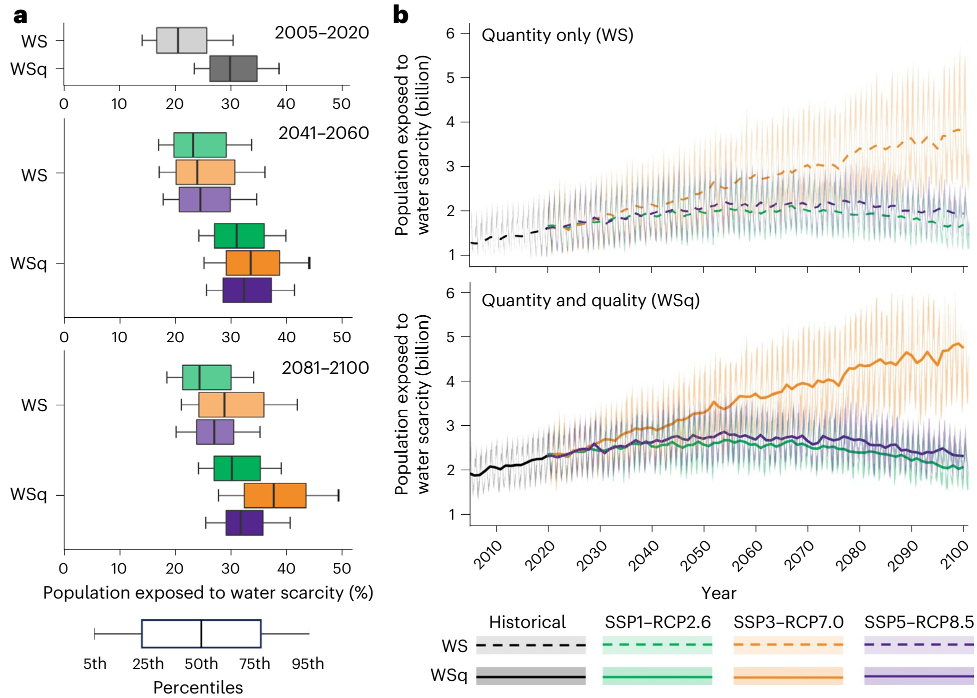

Fig. 3 | Global population exposure to water scarcity under uncertain climate and socio-economic change. **a**, Proportion of the population exposed to water scarcity based on WS and WSq indicators. The box and whisker plots are based on monthly exposure to water scarcity across all GCMs for a historical reference period (2005–2020, top) and under three global change scenarios for the mid-century (2041–2060, middle) and the end of the century (2081–2100, bottom). **b**, The number of people exposed to water scarcity from 2005–2100 based on WS (top) and WSq (bottom) under three global change scenarios. Thick (thin) lines show the annual (monthly) average exposure to water scarcity, and the shaded envelopes (monthly exposure only) represent uncertainty arising from variations in GCM simulations (±1 s.d.). Individual plots for a ll world regions are displayed in Extended Data Figs. 1a–8a.

steps[5,28], there is no overriding consensus in the literature with respect to the spatial scale of analysis[29] (Supplementary Discussion and Supplementary Table 5). Large variability in water scarcity estimates also exists due to factors such as: (1) large diversity in the methodologies used to quantify water scarcity, in particular the indicators used; (2) variability in how results are reported; and (3) the time periods used for reporting.

Few assessments have comprehensively evaluated population exposure to future water scarcity. The global urban population exposed to water scarcity in 2050 was estimated at 1.7–2.7 billion people[18], comparable to our WS estimate (2.0–2.5 billion people). When also including surface water quality (WSq), however, our estimates of population exposure in 2050 increased to 2.6–3.3 billion, with disproportionate impacts on populations located in the Global South. In ref. 27 it was estimated that 57% of people will suffer water scarcity at least one month per year by 2050[27]. This is probably an underestimate, in part due to the poor representation of water pollution[30]. Our estimates of exposure to WSq at least one month per year in 2050 are somewhat higher at 56–62% (4.7–6.1 billion people). However, it should be noted that the absolute numbers of population exposure are strongly influenced by the population projections (associated with the SSPs).

The uncertainty in water scarcity projections was assessed using an ensemble of 15 model runs based on: (1) five global climate models; and (2) three combined socio-economic–climate scenarios. We therefore neglected uncertainty arising from the model parameterizations and inaccuracies in the representation of physical processes within both the GHM (PCR-GLOBWB 2) and the surface water quality model (DynQual). Assessments of water scarcity have been shown to be sensitive to the GHM[17] used. However, while many existing GHMs have the capability to assess quantity-driven water scarcity[17], few global surface water quality models exist[31]—especially models that operate with the high spatial and temporal resolutions needed for water scarcity assessments[3,28,32].

A huge range of water quality constituents can influence the usability of water for different sectoral purposes, far beyond the three considered in this study (total dissolved solids, biological oxygen demand and faecal coliform loadings). Increasing efforts to understand global surface water quality, supported by initiatives from the World Water Quality Alliance, the Inter-Sectoral Impact Model Intercomparison Project and Process-Based Models for Climate Impact Attribution Across Sectors, will improve the representation of water quality (for example, more water quality constituents, improved understanding of 'safe' thresholds) in subsequent water scarcity assessments. Similar to surface water quality, there are increasing efforts to improve our understanding of the quality of groundwater sources globally. For example, promising results were obtained using machine learning to assess global arsenic concentrations in groundwater, which estimated that between 94 and 220 million people are potentially exposed[33]. However, knowledge of global groundwater quality is still severely lacking, and the monitoring data for groundwater quality needed for model training and validation are highly limited. Our study therefore relies on the (erroneous) assumption that all groundwater abstracted is of sufficient quality for the sectoral user (that is, there is no grey water footprint associated with groundwater), potentially leading to an underestimation of clean water scarcity. While high-resolution global-scale groundwater models[34] may provide a basis for modelling groundwater quality, further developments are required before this can be included in water scarcity assessments.

Clean water technologies, such as desalination[35] and treated wastewater reuse[36], are increasingly being used to supplement conventional water supplies and mitigate water scarcity issues. While theoretical maximum expansions in desalination and treated wastewater reuse have potential to significantly reduce global water scarcity levels[2], quantitative projections of how these technologies will develop in the future are lacking. Future work should therefore aim to

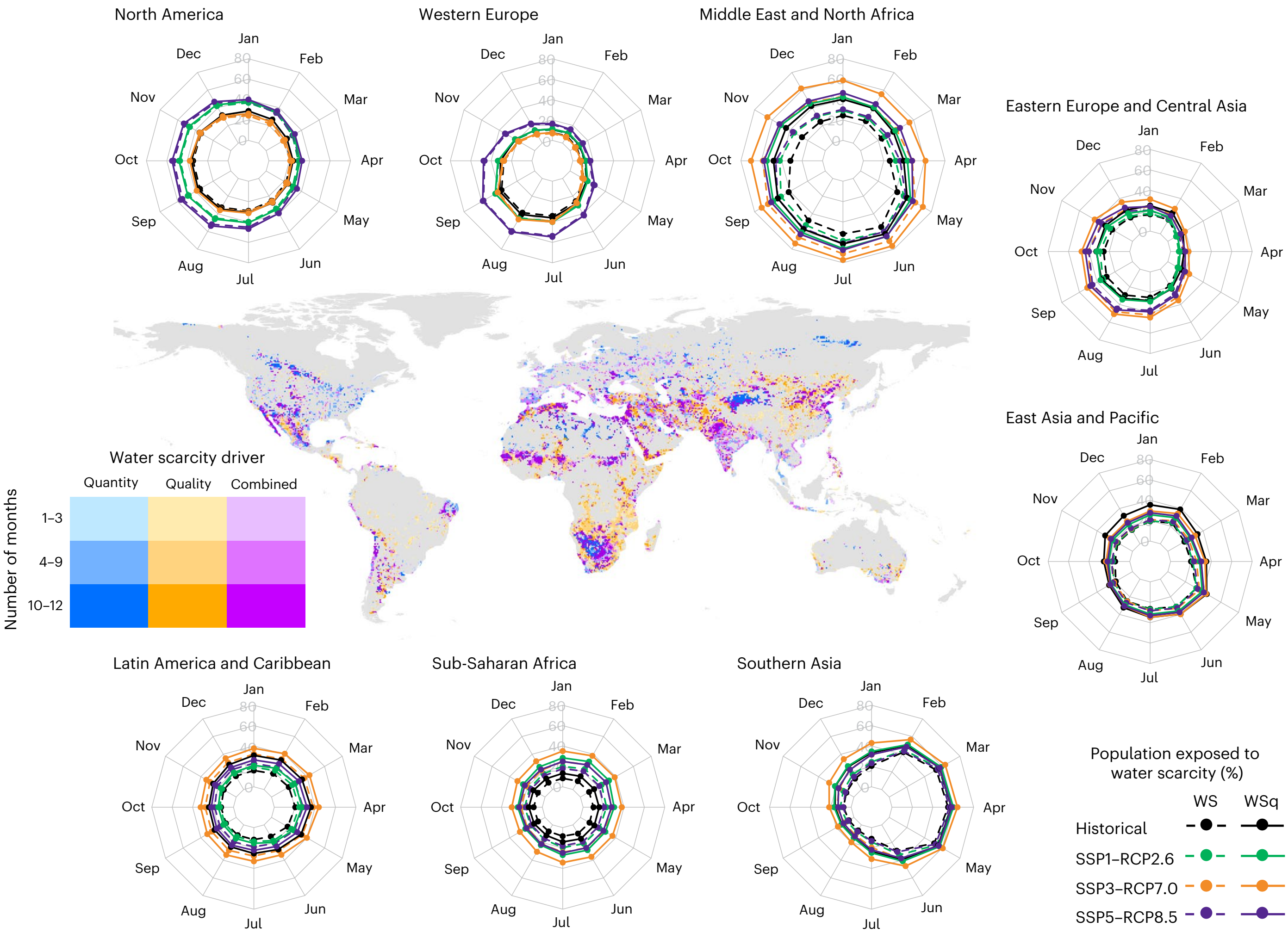

Fig. 4 | Regional exposure to water scarcity and key drivers at the end of the twenty-first century under uncertain climate and socio-economic change. The map displays water quality hotspots and their drivers. Hotspots are colour coded to show the number of months that conditions of water scarcity exist per year averaged for the end of the century (2081–2100) under SSP3–RCP7.0. Radar plots display the proportion of the population in each world region exposed to water scarcity in each month based WS and WSq indicators averaged at the end of the century (2081–2100) under three global change scenarios and five GCMs. Map shapefile from The World Bank under a Creative Commons license CC BY 4.0.

quantify the provision of desalination and treated wastewater reuse under various socio-economic and climatic changes, and quantify their impact on the alleviation of both quantity- and quality-driven water scarcity.

Addressing these challenges, in addition to better accounting for the impact of structural uncertainty in global hydrological and water quality models on water scarcity estimates, should form the basis of improving quantifications of (future) clean water scarcity. Furthermore, by introducing water quality into the water scarcity assessment, we still only represent aspects related to physical water scarcity. Water scarcity issues related to access and equity of distribution, in addition to the adaptive capacity of populations, are overlooked. Improved representation of these dimensions is also essential for the development of viable response strategies for both mitigation and adaptation to address the increasing challenges posed by global water scarcity.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-024-02007-0.

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Methods

Coupled hydrological and surface water quality modelling

Simulations from a coupled global hydrological model (PCR-GLOBWB 2)[37] and surface water quality model (DynQual)[21,22] formed the basis of our water scarcity quantifications. PCR-GLOBWB 2 and DynQual are high-spatiotemporal-resolution (5 arcmin gridded; daily time step) process-based models with global extent, and full model descriptions have been published[21,22,37]. For each grid cell and time step, PCR-GLOBWB 2 simulates soil moisture in two vertically stacked upper soil layers, and water exchange between the soil, atmosphere and the underlying groundwater reservoir[37]. Runoff is partitioned into surface runoff, interflow and groundwater recharge, with routing of water across the river network simulated using the kinematic wave approximation[37]. Human water use (domestic, industrial, irrigation and livestock) is fully integrated within the hydrological model at each time step.

DynQual simulates water temperature, salinity as indicated by total dissolved solids (TDS), organic pollution indicated by biological oxygen demand (BOD) and pathogen pollution indicated by faecal coliform concentrations. DynQual extends the representation of human–water interactions in PCR-GLOBWB 2, which includes sectoral water demands, actual abstractions from surface waters and groundwater (that is, subject to the availability of these resources) and consumptive water use[37] to also consider return flows from these sectors as sources of surface water pollution. To this end, a mass balance approach is used to accumulate and route loadings of TDS, BOD and faecal coliform through the stream network[22]. DynQual simulates water quality per grid cell over a consecutive series of discrete time periods, with each grid cell containing a volume element and a (fully mixed) pollutant mass[22]. PCR-GLOBWB 2–DynQual therefore accounts for the synergetic nature of water quality and quantity, with simulated concentrations computed for each time step considering both the dilution capacity and pollutant-specific decay processes. Although limited water quality and discharge monitoring data are available for certain regions (for example, large parts of Africa, central Asia) both PCR-GLOBWB 2 and DynQual have been extensively validated against monitoring data, representing different hydroclimatic regions with different anthropogenic impacts[21,22,37].

Water demands, water availability and surface water quality under global change

Water scarcity quantifications were made using monthly PCR-GLOBWB 2–DynQual output of sectoral water demands (for example, domestic, industrial, livestock and irrigation), water availability (for example, discharge) and water quality (TDS, BOD and faecal coliform concentrations) from 2005–2100[38]. Three combined SSP–RCP scenarios (SSP1–RCP2.6, SSP3–RCP7.0 and SSP5–RCP8.5), each of which simulated with bias-corrected climate input from five GCMs (GFDL-ESM4; UKESM1-0-LL; MPI-ESM1-2-hr; IPSL-CM6A-LR and MRI-ESM2-0), were used to consider a range of possible future conditions and to capture uncertainty inherent in the climatological (GCM) projections.

The input data underpinning the above simulations are fully described in previous work[38] and briefly summarized below. Meteorological forcing required for PCR-GLOBWB 2 included precipitation, temperature and reference evaporation, which were taken from each combined SSP–RCP scenario from ISIMIP3b[39]. The socio-economic data (for example, gridded population, urban fraction, livestock numbers, excretion rates and effluent concentrations) used for estimating sectoral pollutant loadings were from various sources[2,21,22,24,37,40–45]. In addition to the socio-economic drivers, the presence and effectiveness of wastewater management practices can also strongly influence the eventual pollutant loadings to the stream network. The development of wastewater practices, split into three categories ((1) collection and treatment (primary, secondary, tertiary and quaternary); (2) collected but untreated; and (3) uncollected (basic sanitation and open defecation)) are elaborated on under the three different SSPs with a decadal time step at the country level[46], and downscaled to 5 arcmin following procedures from previous work[21,22]. Technological improvements in pollutant removal efficiencies were accounted for in the designation of 'quaternary treatment', per the wastewater treatment practices dataset[46].

Water scarcity indicators

Existing water scarcity assessments predominantly build on the concepts of water shortage (that is, renewable water availability per capita[47,48] and/or water stress (the ratio of water use to renewable water availability))[13,49]. In this study, and per the UN key indicator of water stress or security (Sustainable Development Indicator 6.4.2), we used the criticality ratio to assess water scarcity from a quantity perspective, also accounting for environmental flow requirements and the current provision of water from unconventional water resources (that is, desalination and treated wastewater reuse) using equation (1).

$$\mathrm{WS} = \frac{\sum D_j - \mathrm{GWA} - \mathrm{UWR}}{Q - \mathrm{EFR}} \tag{1}$$

WS represents water scarcity considering water quantity only (unitless), D_j represents the gross water demands for sector j (in m^3 month^{-1}) for which the domestic, industrial, livestock and irrigation sectors are considered; GWA represents groundwater abstractions to fulfil sectoral demands (in m^3 month^{-1}); UWR represents the current water supply (in m^3 month^{-1}) from unconventional water resources to fulfil sectoral demands (desalination for the domestic and industrial sectors; treated wastewater reuse for the irrigation sector); Q is discharge (m^3 month^{-1}); and EFR is the environmental flow requirement (in m^3 month^{-1}) calculated using the monthly variable flow method, which prescribes EFRs with respect to the mean annual flow (MAF)[50]. EFRs were set at 60%, 45% and 30% of monthly flow under low (defined as ≤40% of the MAF), intermediate (40–80% of the MAF) and high (>80% of the MAF) flow conditions, respectively.

Quality-induced water scarcity was evaluated using the concept of the grey water footprint[1,2,8,11,51]. The grey water footprint represents the volume of water required to assimilate pollution to meet ambient water quality standards via dilution[52]. While this dilution does not necessarily take place in reality, the purpose of this approach is to estimate a fresh water equivalent to facilitate a comparable measure of quantity and quality aspects for water scarcity assessment[51]. Building on previous work[2], WSq was calculated using equation (2).

$$\mathrm{WSq} = \mathrm{WS} + \frac{\max(\mathrm{dq}_{j,p})}{Q}$$

$$\mathrm{dq}_{j,p} = \begin{cases} 0, & C_p \le C\max_{j,p} \\ \left(\frac{(D_j - \mathrm{GWA} - \mathrm{UWR})\cdot C_p}{C\max_{j,p}} - (D_j - \mathrm{GWA} - \mathrm{UWR})\right), & C_p > C\max_{j,p} \end{cases} \tag{2}$$

WSq represents water scarcity including both water quantity and quality (unitless); $\mathrm{dq}_{j,p}$ is the additional water required to achieve acceptable water quality for sector j and water quality constituent p via dilution; C_p is the surface water concentration of water quality constituent p (TDS and BOD in mg l^{-1}; faecal coliform concentration in colony-forming units per 100 ml) and $C\max_{j,p}$ is the maximum permissible concentration of water quality constituent p for sectoral use j (TDS: 2,000, 7,000, 2,000 and 2,100 mg l^{-1}; BOD: 5, 15, 8 and 30 mg l^{-1}; faecal coliform concentration: 1,000, 5,000, 2,000 and 5,000 colony-forming units per 100 ml for the domestic, industrial, livestock and irrigation sectors, respectively), following thresholds used in previous work[21,38,45]. All other terms follow those in equation (1).

Water scarcity quantifications

Water scarcity based on WS and WSq was evaluated at monthly time steps over the period 2005–2100 considering three combined SSP–RCP combinations and five GCMs. Although many water scarcity assessments have been conducted on an annual timescale[5], we evaluated WS and WSq on a monthly time step to better represent the substantial intra-annual variations in water availability, demand and quality. Following most water quality assessments, we estimated the numbers and percentages of people exposed to water scarcity under these scenarios—aggregated at both the global scale and for each geographic region (Supplementary Fig. 1). Although all model simulations were made at 5 arcmin (gridded) resolution, water scarcity was evaluated using abstraction zones as the spatial unit. Abstraction zones are inherent to the water demand module of PCR-GLOBWB 2, representing groups of grid cells that relate water availability to human demands and therefore better match local demands to available water resources in nearby grid cells. WS and WSq values exceeding 1 were used to indicate water scarcity—that is, the demands for water resources (minus those met by groundwater pumping or unconventional water resources) exceeded the renewable water availability (minus the water required to maintain environmental flows). Our indicators therefore focused on physical (clean) water scarcity only, without consideration of other important dimensions of water scarcity (such as economic factors, access)[5].

Data availability
Output data from this study (that is, population exposure to water scarcity) per geographic region are available via Figshare at https://doi.org/10.6084/m9.figshare.24866310.v1 (ref. 53). Water quantity and quality data are available via Zenodo at https://doi.org/10.5281/zenodo.7811612 (ref. 54).

Code availability
The coupled global hydrological model and water resources model (PCR-GLOBWB 2) and global surface water quality model (DynQual) are freely available via Zenodo at https://doi.org/10.5281/zenodo.7932317 (ref. 55) and via GitHub at https://github.com/UU-Hydro/.

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Author contributions
The study was designed by E.R.J., M.F.P.B. and M.T.H.v.V. Data processing, analysis and interpretation were led by E.R.J. in consultation with M.F.P.B. and M.T.H.v.V. E.R.J. led the paper writing, and all authors approved the paper.

Competing interests
The authors declare no competing interests.

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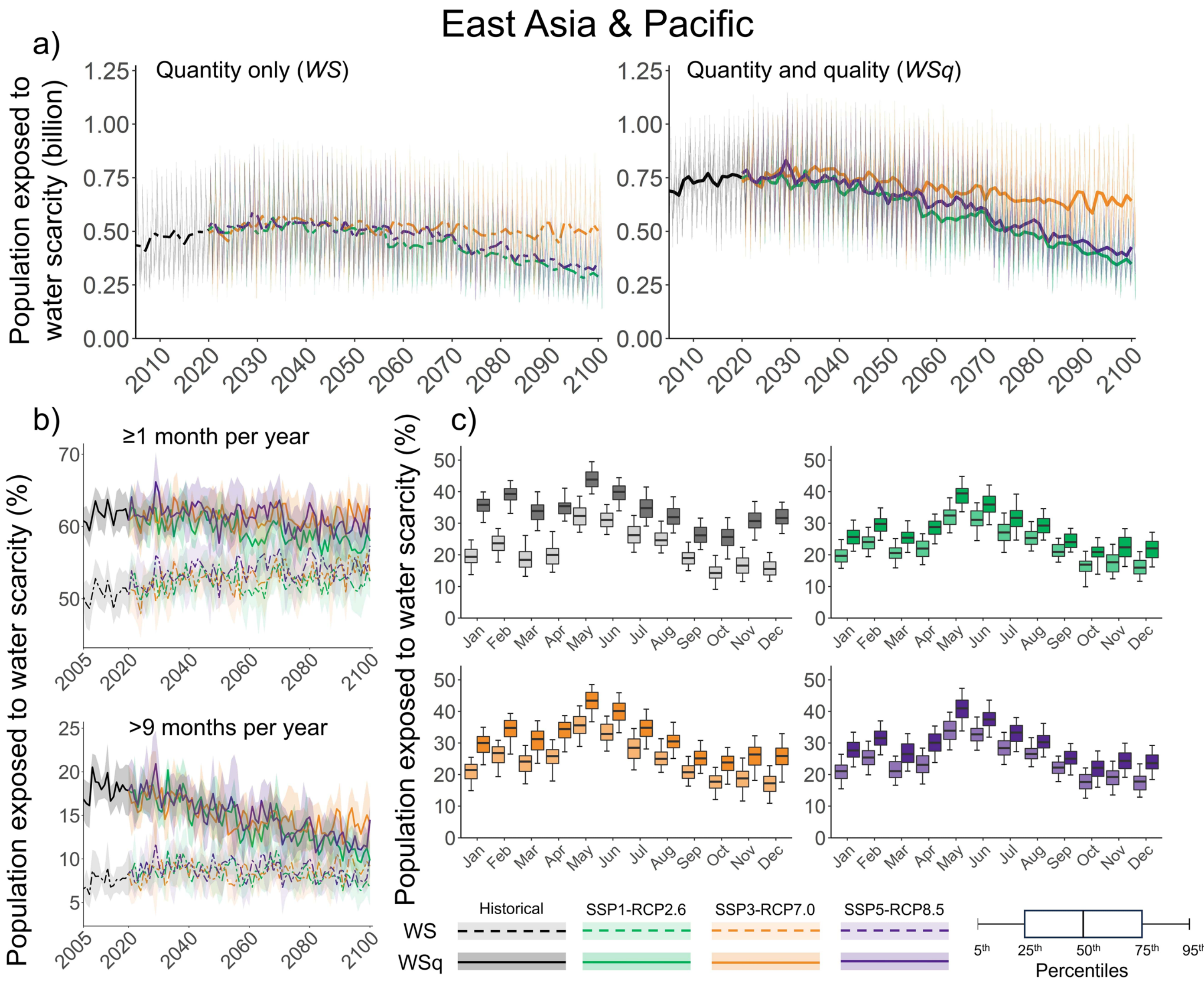

Extended Data Fig. 1 | Population exposure to water scarcity in the East Asia & Pacific region under uncertain climate and socio-economic change. **a)** Number of people exposed to water scarcity from 2005–2100, based on indicators considering water quantity only (*WS*) and including water quality (*WSq*). Thick lines and thin lines display the annual average and monthly average exposure to water scarcity, respectively, while shaded areas represent uncertainty arising from variations in GCM simulations as ±1 s.d. **b)** Percentage of the population exposed to seasonal (that is at least one month per year) and year-round (>9 months per year) water scarcity from 2005–2100, as indicated by *WS* and *WSq*. Lines display the mean average exposure per year averaged over the five GCMs considered, while shaded areas represent uncertainty arising from variations in GCM simulations as ±1 s.d. **c)** Percentage of the population exposed to water scarcity in each month, as indicated by *WS* and *WSq*. Boxplots are made based on monthly exposure to water scarcity across all GCMs for a historical reference period (2005–2020) and under three global change scenarios at the end of the century (2081–2100).

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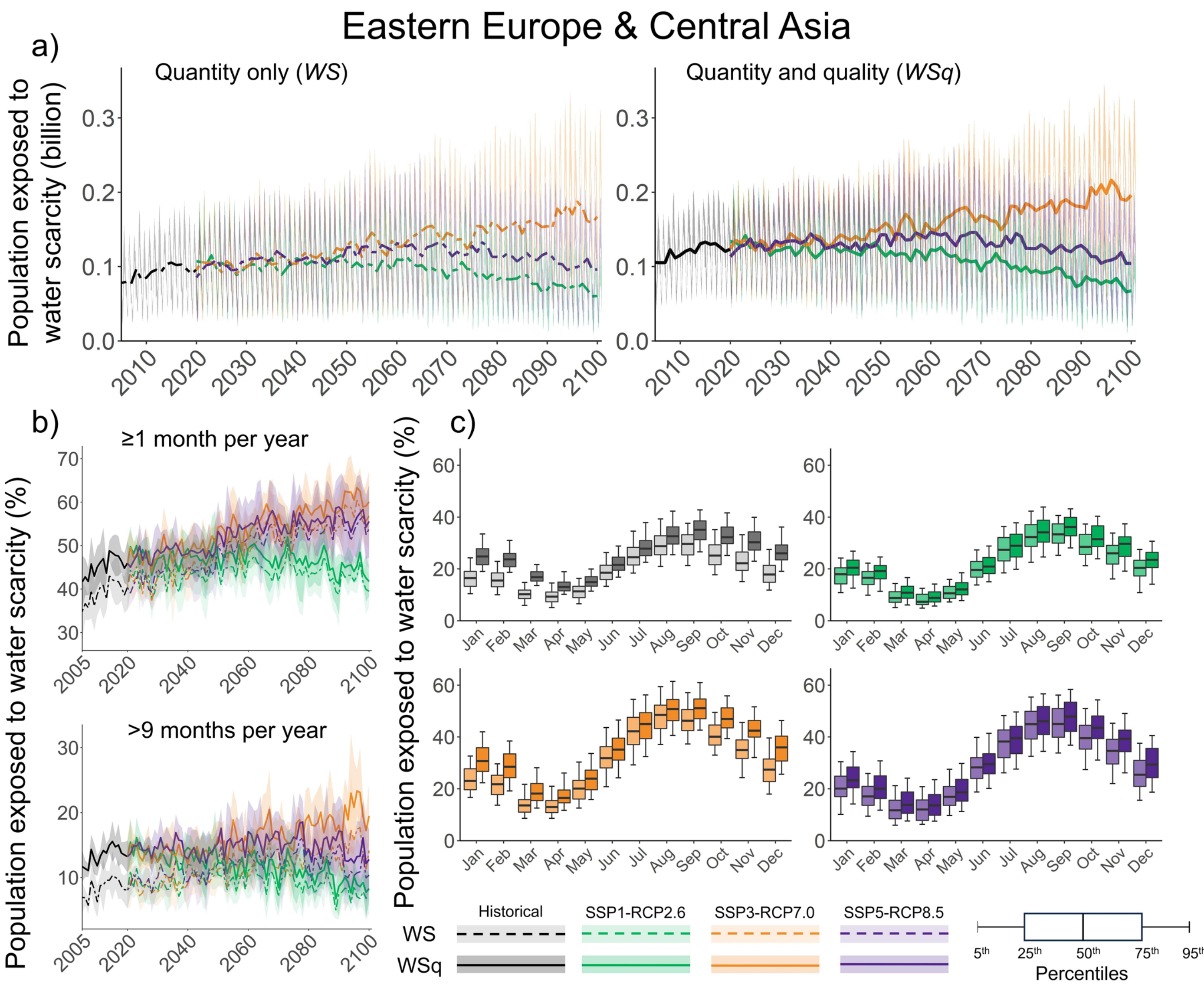

Extended Data Fig. 2 | Population exposure to water scarcity in the Eastern Europe & Central Asia region under uncertain climate and socio-economic change. a) Number of people exposed to water scarcity from 2005–2100, based on indicators considering water quantity only (*WS*) and including water quality (*WSq*). Thick lines and thin lines display the annual average and monthly average exposure to water scarcity, respectively, while shaded areas represent uncertainty arising from variations in GCM simulations as ±1 s.d. **b)** Percentage of the population exposed to seasonal (that is at least one month per year) and year-round (>9 months per year) water scarcity from 2005–2100, as indicated by *WS* and *WSq*. Lines display the mean average exposure per year averaged over the five GCMs considered, while shaded areas represent uncertainty arising from variations in GCM simulations as ±1 s.d. **c)** Percentage of the population exposed to water scarcity in each month, as indicated by *WS* and *WSq*. Boxplots are made based on monthly exposure to water scarcity across all GCMs for a historical reference period (2005–2020) and under three global change scenarios at the end of the century (2081–2100).

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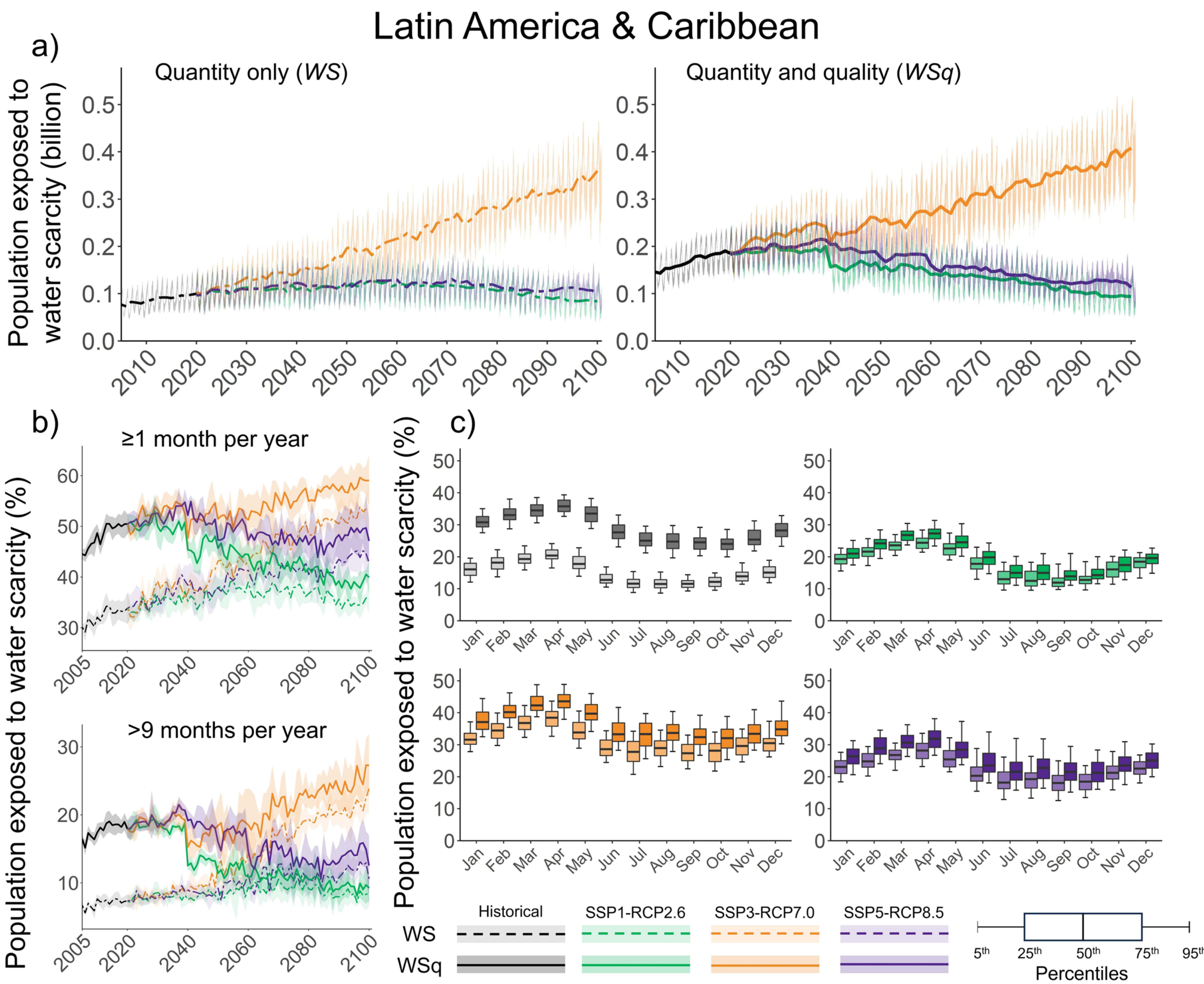

Extended Data Fig. 3 | Population exposure to water scarcity in the Latin America & Caribbean region under uncertain climate and socio-economic change. a) Number of people exposed to water scarcity from 2005–2100, based on indicators considering water quantity only (*WS*) and including water quality (*WSq*). Thick lines and thin lines display the annual average and monthly average exposure to water scarcity, respectively, while shaded areas represent uncertainty arising from variations in GCM simulations as ±1 s.d. **b)** Percentage of the population exposed to seasonal (that is at least one month per year) and year-round (>9 months per year) water scarcity from 2005–2100, as indicated by *WS* and *WSq*. Lines display the mean average exposure per year averaged over the five GCMs considered, while shaded areas represent uncertainty arising from variations in GCM simulations as ±1 s.d. **c)** Percentage of the population exposed to water scarcity in each month, as indicated by *WS* and *WSq*. Boxplots are made based on monthly exposure to water scarcity across all GCMs for a historical reference period (2005–2020) and under three global change scenarios at the end of the century (2081–2100).

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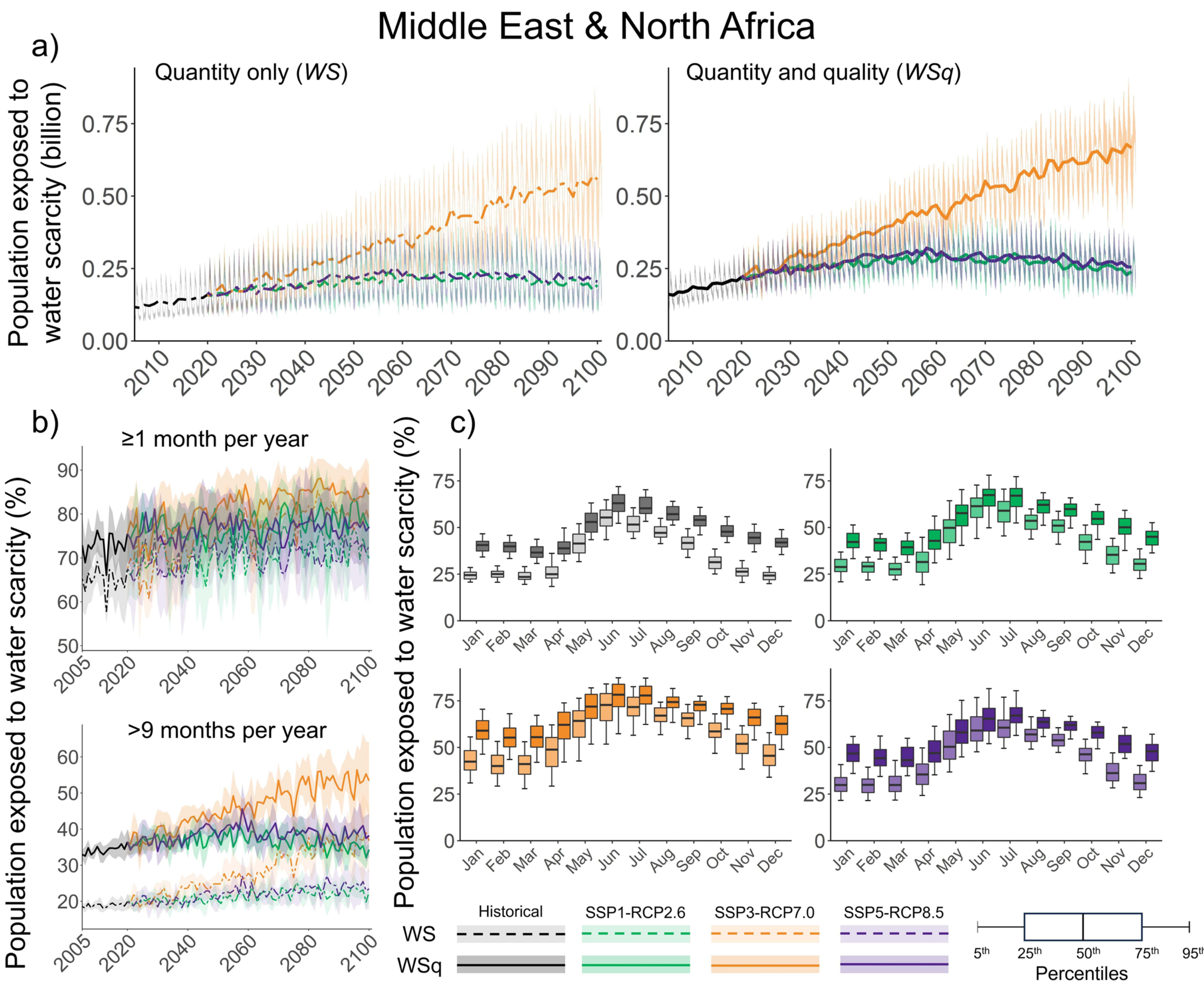

Extended Data Fig. 4 | Population exposure to water scarcity in the Middle East & North Africa region under uncertain climate and socio-economic change. a) Number of people exposed to water scarcity from 2005–2100, based on indicators considering water quantity only (*WS*) and including water quality (*WSq*). Thick lines and thin lines display the annual average and monthly average exposure to water scarcity, respectively, while shaded areas represent uncertainty arising from variations in GCM simulations as ±1 s.d. **b)** Percentage of the population exposed to seasonal (that is at least one month per year) and year-round (>9 months per year) water scarcity from 2005–2100, as indicated by *WS* and *WSq*. Lines display the mean average exposure per year averaged over the five GCMs considered, while shaded areas represent uncertainty arising from variations in GCM simulations as ±1 s.d. **c)** Percentage of the population exposed to water scarcity in each month, as indicated by *WS* and *WSq*. Boxplots are made based on monthly exposure to water scarcity across all GCMs for a historical reference period (2005–2020) and under three global change scenarios at the end of the century (2081–2100).

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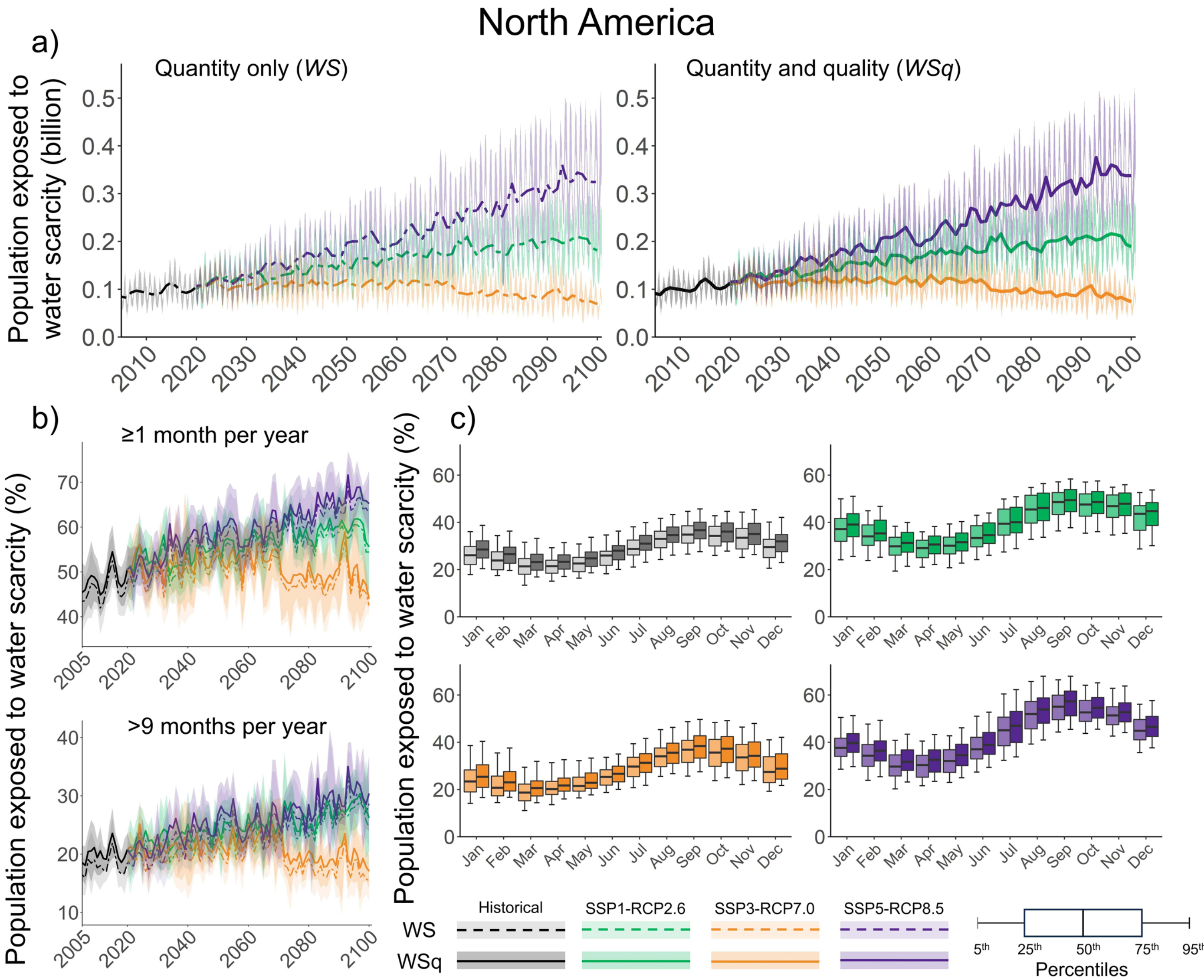

Extended Data Fig. 5 | Population exposure to water scarcity in the North America region under uncertain climate and socio-economic change. **a)** Number of people exposed to water scarcity from 2005–2100, based on indicators considering water quantity only (*WS*) and including water quality (*WSq*). Thick lines and thin lines display the annual average and monthly average exposure to water scarcity, respectively, while shaded areas represent uncertainty arising from variations in GCM simulations as ±1 s.d. **b)** Percentage of the population exposed to seasonal (that is at least one month per year) and year-round (>9 months per year) water scarcity from 2005–2100, as indicated by *WS* and *WSq*. Lines display the mean average exposure per year averaged over the five GCMs considered, while shaded areas represent uncertainty arising from variations in GCM simulations as ±1 s.d. **c)** Percentage of the population exposed to water scarcity in each month, as indicated by *WS* and *WSq*. Boxplots are made based on monthly exposure to water scarcity across all GCMs for a historical reference period (2005–2020) and under three global change scenarios at the end of the century (2081–2100).

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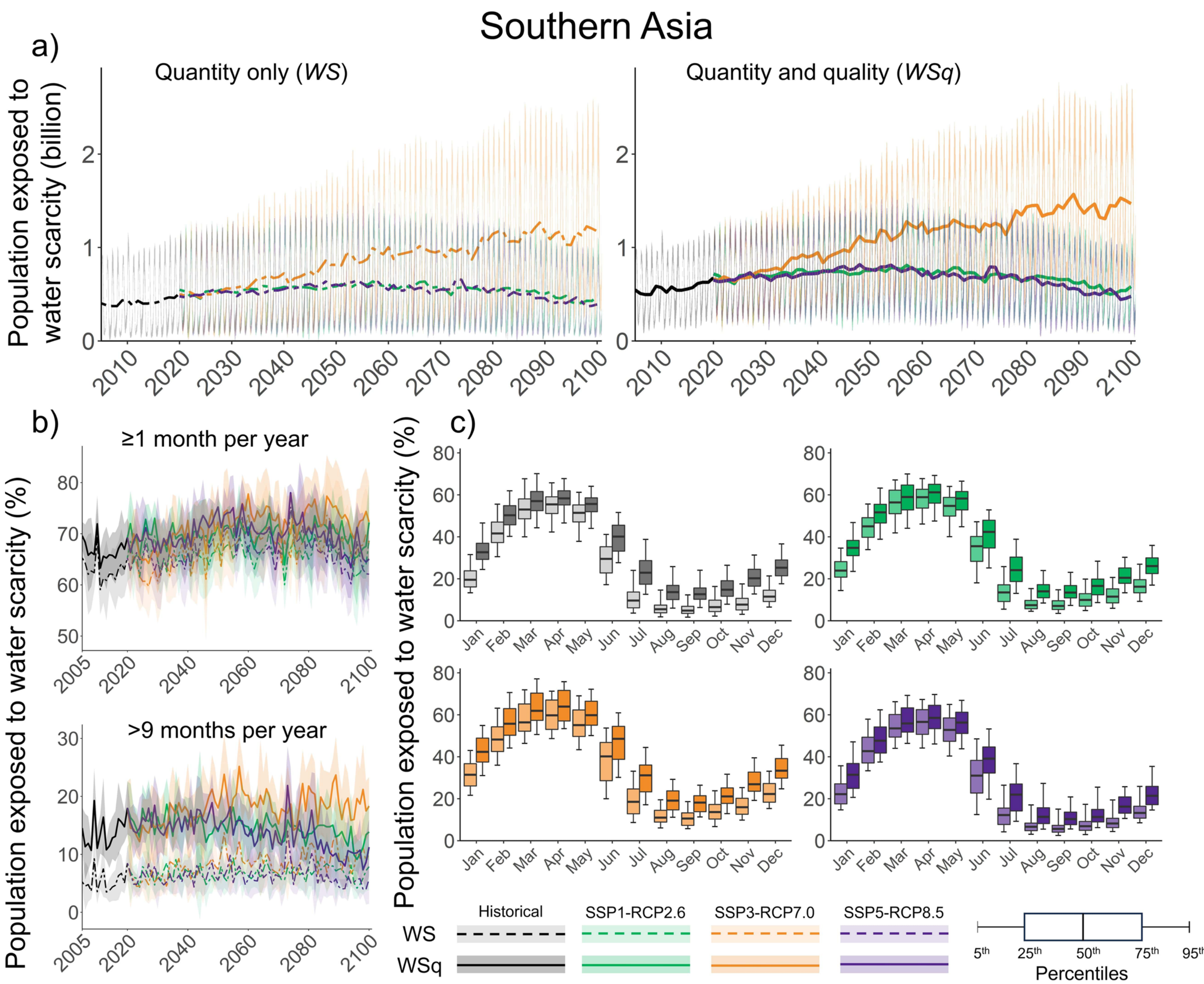

Extended Data Fig. 6 | Population exposure to water scarcity in the Southern Asia region under uncertain climate and socio-economic change. a) Number of people exposed to water scarcity from 2005–2100, based on indicators considering water quantity only (*WS*) and including water quality (*WSq*). Thick lines and thin lines display the annual average and monthly average exposure to water scarcity, respectively, while shaded areas represent uncertainty arising from variations in GCM simulations as ±1 s.d. **b)** Percentage of the population exposed to seasonal (that is at least one month per year) and year-round (>9 months per year) water scarcity from 2005–2100, as indicated by *WS* and *WSq*. Lines display the mean average exposure per year averaged over the five GCMs considered, while shaded areas represent uncertainty arising from variations in GCM simulations as ±1 s.d. **c)** Percentage of the population exposed to water scarcity in each month, as indicated by *WS* and *WSq*. Boxplots are made based on monthly exposure to water scarcity across all GCMs for a historical reference period (2005–2020) and under three global change scenarios at the end of the century (2081–2100).

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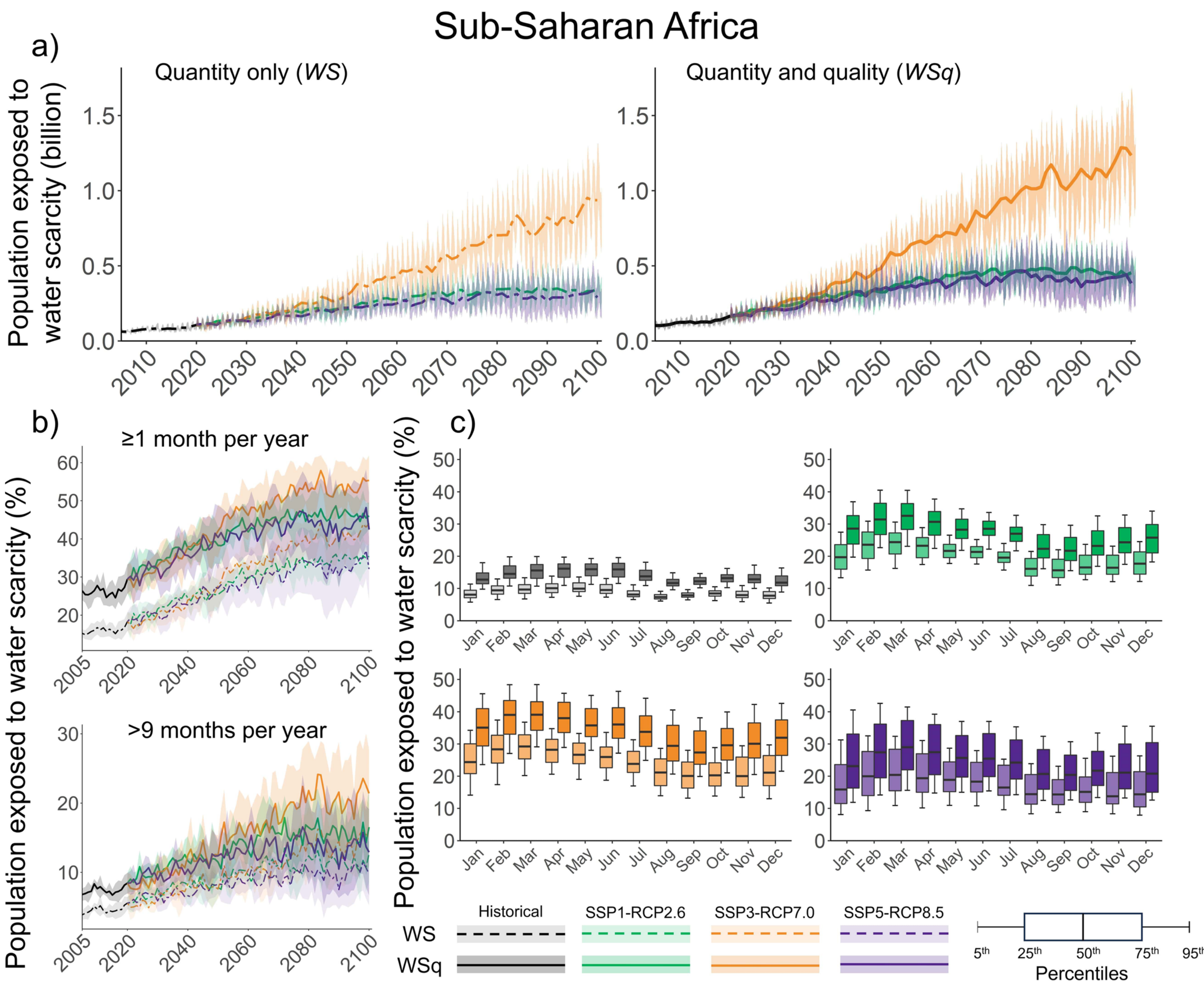

Extended Data Fig. 7 | Population exposure to water scarcity in the Sub-Saharan Africa region under uncertain climate and socio-economic change. **a)** Number of people exposed to water scarcity from 2005–2100, based on indicators considering water quantity only (*WS*) and including water quality (*WSq*). Thick lines and thin lines display the annual average and monthly average exposure to water scarcity, respectively, while shaded areas represent uncertainty arising from variations in GCM simulations as ±1 s.d. **b)** Percentage of the population exposed to seasonal (that is at least one month per year) and year-round (>9 months per year) water scarcity from 2005–2100, as indicated by *WS* and *WSq*. Lines display the mean average exposure per year averaged over the five GCMs considered, while shaded areas represent uncertainty arising from variations in GCM simulations as ±1 s.d. **c)** Percentage of the population exposed to water scarcity in each month, as indicated by *WS* and *WSq*. Boxplots are made based on monthly exposure to water scarcity across all GCMs for a historical reference period (2005–2020) and under three global change scenarios at the end of the century (2081–2100).

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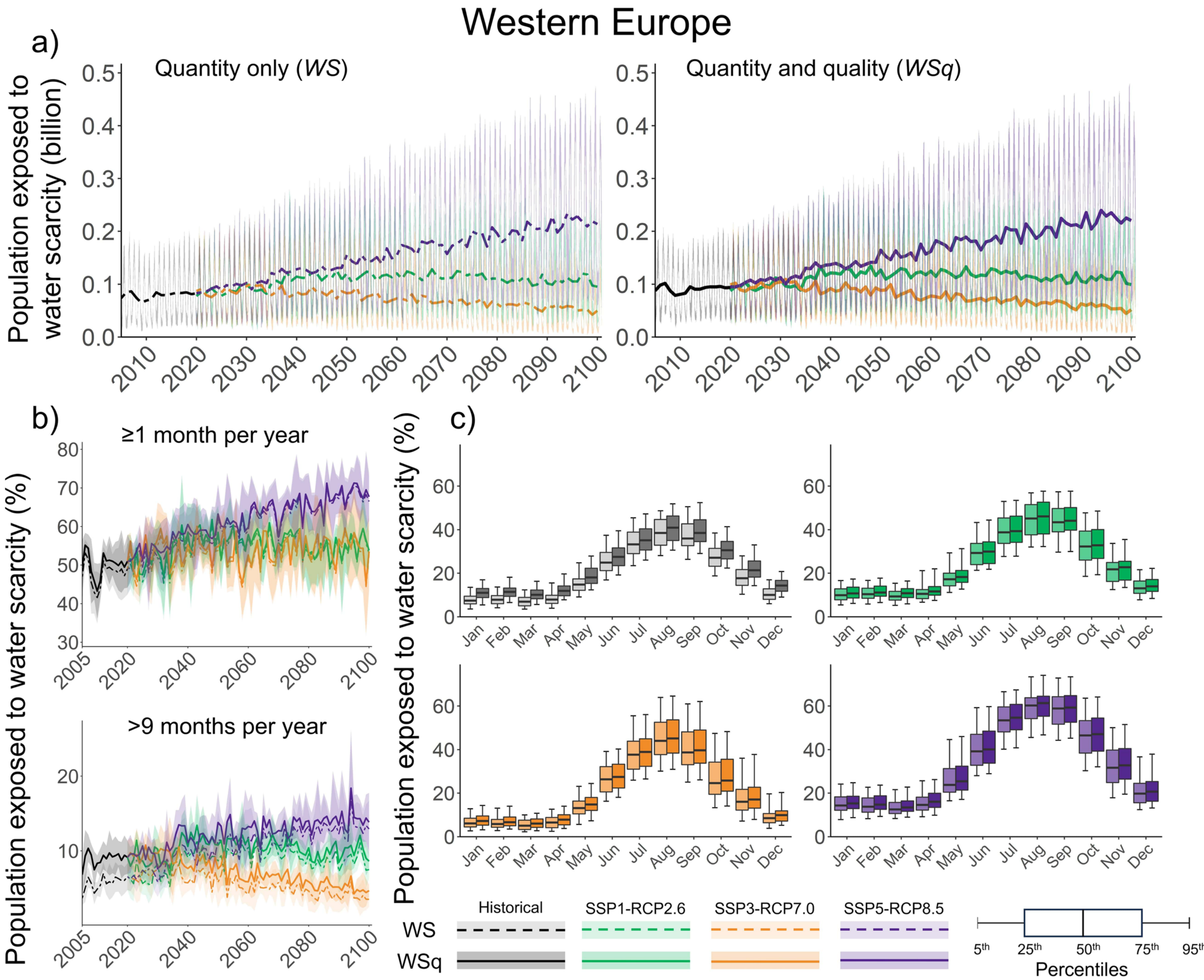

Extended Data Fig. 8 | Population exposure to water scarcity in the Western Europe region under uncertain climate and socio-economic change. **a)** Number of people exposed to water scarcity from 2005–2100, based on indicators considering water quantity only (*WS*) and including water quality (*WSq*). Thick lines and thin lines display the annual average and monthly average exposure to water scarcity, respectively, while shaded areas represent uncertainty arising from variations in GCM simulations as ±1 s.d. **b)** Percentage of the population exposed to seasonal (that is at least one month per year) and year-round (>9 months per year) water scarcity from 2005–2100, as indicated by *WS* and *WSq*. Lines display the mean average exposure per year averaged over the five GCMs considered, while shaded areas represent uncertainty arising from variations in GCM simulations as ±1 s.d. **c)** Percentage of the population exposed to water scarcity in each month, as indicated by *WS* and *WSq*. Boxplots are made based on monthly exposure to water scarcity across all GCMs for a historical reference period (2005–2020) and under three global change scenarios at the end of the century (2081–2100).

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Extended Data Table 1 | Future population exposure to water scarcity

Region	Population exposure to water scarcity (*WS*) at least 1 month per year (%)						
	Historical	2041 – 2060			2081 – 2100		
		SSP1-RCP2.6	SSP3-RCP7.0	SSP5-RCP8.5	SSP1-RCP2.6	SSP3-RCP7.0	SSP5-RCP8.5
Global	47.3 *(46.1 - 48.2)*	51.0 *(49.7- 52.9)*	52.1 *(49.7 - 54.5)*	52.8 *(51.3 - 54.3)*	51.7 *(50.1 - 53.1)*	56.7 *(54.5 - 59.3)*	54.3 *(52.2 - 56.7)*
East Asia & Pacific	50.7 *(48.7 – 52.6)*	52.5 *(50.5 – 54.6)*	52.5 *(50.8 – 54.5)*	54.0 *(51.9 – 56.1)*	52.4 *(50.4 – 54.7)*	54.0 *(51.4 – 56.5)*	54.4 *(52.7 – 56.1)*
Eastern Europe & Central Asia	39.3 *(35.6 – 42.4)*	44.2 *(40.7 – 47.5)*	47.7 *(44.2 – 50.7)*	47.4 *(41.8 – 52.1)*	42.8 *(39.7 – 45.8)*	56.0 *(51.7 – 59.5)*	54.1 *(48.1 – 59.5)*
Latin America & Caribbean	32.3 *(30.6 – 33.9)*	36.9 *(35 – 38.5)*	40.8 *(38.3 – 42.9)*	38.7 *(36.2 – 41.1)*	35.7 *(33.9 – 37)*	51.4 *(49.2 – 53.1)*	42.6 *(40 – 45.7)*
Middle East & North Africa	65.1 *(59.8 – 70.4)*	69.4 *(65.4 – 75.5)*	75.9 *(70.8 – 81.1)*	72.0 *(67 – 78.2)*	72.4 *(69.1 – 77.8)*	80.4 *(75.4 – 85.9)*	71.5 *(65.8 – 78.6)*
North America	46.2 *(42.4 – 50.4)*	53.8 *(49.7 – 58.1)*	51.0 *(46.3 – 55.5)*	56.5 *(53 – 60.7)*	58.1 *(54.5 – 62.4)*	47.6 *(41.9 – 52.7)*	63.9 *(59.7 – 67.3)*
Southern Asia	63.0 *(59.5 – 66.5)*	66.4 *(62.6 – 69.9)*	67.5 *(64.1 – 72.3)*	68.9 *(65.7 – 71.8)*	66.2 *(63.6 – 70.9)*	69.1 *(62.8 – 75.4)*	64.9 *(60.5 – 69.5)*
Sub-Saharan Africa	16.1 *(14.4 – 17.7)*	27.2 *(24.8 – 29.5)*	28.9 *(24.9 – 32.8)*	26.5 *(23.1 – 29.9)*	34.7 *(31.4 – 38)*	41.2 *(38.3 – 45.3)*	32.7 *(26.3 – 40.9)*
Western Europe	47.9 *(43 – 53.2)*	55.8 *(51.3 – 60.7)*	52.4 *(47.4 – 57.6)*	58.4 *(53.7 – 62.4)*	53.9 *(49 – 58.8)*	53.8 *(47.1 – 61.6)*	66.7 *(62.3 – 70.9)*

Values in parentheses indicate the variability in exposure to water scarcity across individual years within the aggregated time periods, combined with uncertainties in GCM simulations, as the 25th and 75th percentile values.