The imbalance of the Asian water tower

Tandong Yao[1] ✉, Tobias Bolch[2], Deliang Chen[3], Jing Gao[1], Walter Immerzeel[4], Shilong Piao[1,5], Fengge Su[1], Lonnie Thompson[6], Yoshihide Wada[7], Lei Wang[1], Tao Wang[1], Guangjian Wu[1], Baiqing Xu[1], Wei Yang[1], Guoqing Zhang[1] ✉ and Ping Zhao[8]

Abstract | The Hindu Kush–Karakoram–Himalayan system, named the Third Pole because it is the largest global store of frozen water after the polar regions, provides a reliable water supply to almost 2 billion people. Marked atmospheric warming has changed the balance of this so-called Asian water tower and altered water resources in downstream countries. In this Review, we synthesize observational evidence and model projections that describe an imbalance in the Asian water tower caused by accelerated transformation of ice and snow into liquid water. This phase change is associated with a south–north disparity due to the spatio-temporal interaction between the westerlies and the Indian monsoon. A corresponding spatial imbalance is exhibited by alterations in freshwater resources in endorheic or exorheic basins. Global warming is expected to amplify this imbalance, alleviating water scarcity in the Yellow and Yangtze River basins and increasing scarcity in the Indus and Amu Darya River basins. However, the future of the Asian water tower remains highly uncertain. Accurate predictions of future water supply require the establishment of comprehensive monitoring stations in data-scarce regions and the development of advanced coupled atmosphere–cryosphere–hydrology models. Such models are needed to inform the development of actionable policies for sustainable water resource management.

The Tibetan Plateau and surrounding Hindu Kush, Karakoram and Himalayan mountain ranges are nicknamed the Third Pole because they comprise the largest global store of frozen water after the polar regions. This region functions as a water distribution system termed the Asian water tower (AWT)[1] (BOX 1) that delivers water to almost 2 billion people. Abundant glacier ice reservoirs and alpine lakes supply freshwater, and an extended river system encompassing the Yellow, Yangtze, Indus, Mekong, Salween, Ganges, Yarlung Zangbo, Amu Darya, Syr Darya and Tarim Rivers supply freshwater to downstream areas. Over a long history, the AWT has maintained an equilibrium of water resources between liquid and solid states and among different reservoirs. This balance is essential for the reliability and sustainability of the AWT.

However, climate changes since the 1980s threaten this equilibrium. For instance, warming rates in the region are twice the global average[2,3] and precipitation regimes have shifted, increasing in the north-west and decreasing in the south[4–6]. These drastic changes have resulted in shifts in glacier and snow melt[5,7–10], the size and distribution of alpine lakes[11–18] and river run-off[19–21]. These shifts all show marked spatial variability resulting in the redistribution of freshwater between reservoirs[5,11]. At the same time, warming and increasing regional precipitation has caused the treeline to expand towards higher elevations[22]; substantial greening[23] was identified in the AWT region during 1982–2015 (REF.[24]), particularly in the early summer in the south-east[25], and these changes provide strong positive feedback to the regional hydrological responses of freshwater reservoirs in the AWT. Together, these changes imply an increasing imbalance of the AWT in both reservoir status (solid versus liquid) and spatial distribution, which potentially affect both spatio-temporal variations of the local ecosystem and water supply to downstream regions.

Given the reliance of downstream societies on upstream water resources, this imbalance in the AWT will exacerbate already serious issues such as future irrigation needs, conflict between India and Pakistan[1,7,26–29], threats to transportation (including events such as the Zonag Lake outburst[30] and landslides[31] affecting the Qinghai–Tibet and Karakoram highways) and loss of life caused by massive glacier ice collapses such as the 2021 event in India[32]. Most countries in areas downstream of the AWT are developing nations with a high vulnerability to changes in the water supply owing to rapid population growth and socio-economic development[33]. However, current understanding and capacity to predict

✉e-mail: tdyao@itpcas.ac.cn; guoqing.zhang@itpcas.ac.cn

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Key points

- During 1980–2018, warming of the Asian Water Tower (AWT) was 0.42 °C per decade, twice the global average rate.
- Annual precipitation in the AWT increased by 11 mm per decade in endorheic basins and 12 mm per decade in exorheic basins, despite decreased precipitation in some large river basins.
- From 2000 to 2018, total glacier mass in the AWT decreased by about 340 Gt whereas total water mass in lakes increased by 166 Gt.
- Changes in the westerlies and the Indian monsoon led the AWT to develop an imbalance characterized by water gains in endorheic basins and water losses in exorheic basins.
- Ubiquitous increases in precipitation and river run-off are projected in the future of the AWT; however, these changes cannot meet the accelerating water demands of downstream regions and countries.
- Comprehensive monitoring systems, advanced modelling capacity and sustainable water management are needed to develop adaptation policies for the AWT through collaboration between upstream and downstream regions and countries.

the consequences of this imbalance in the AWT are still poor, particularly considering the considerable spatial variations in hydrological, ecological and socio-economic factors between these different regions[1]. Policymakers require critical information on regional hydrological responses to implement, for example, China's pledge of carbon neutrality by 2060 (REF.[34]), and to safeguard the sustainability of the Tibetan Plateau's ecosystems. Such policy decisions require an improved understanding of the current imbalances between glaciers, lakes and rivers, as well as the effects of projected changes to future water supplies and demand.

In this Review, we describe long-term in situ and satellite observations that quantify changes in atmospheric water and freshwater (glaciers, lakes and rivers) constituents of the AWT, and discuss model simulations of their projected future changes. We evaluate how these changes are likely to affect freshwater resources and associated vulnerable societies across downstream basins. We conclude by outlining current knowledge gaps and recommendations for future research.

Observed changes

Marked changes have been observed in the AWT since reliable measurements began in the 1980s (Supplementary Table 1). These changes in precipitation, glaciers and lakes have resulted in shifts to the overall water balance.

Evidence of warming. The AWT has experienced considerable warming beginning in the mid-1950s (REF.[35]), and the warming rate in this region since the 1980s is unparalleled in the past two millennia[2,36]. Observations from meteorological stations show that the annual temperature over the AWT increased by ~0.44 °C per decade during 1979–2020 (REFS[11,37,38]), which was twice as fast as the global average rate (0.19 °C per decade)[39]. The warming rate nearly tripled from 0.16 °C per decade during 1955–1996 (REF.[35]) to 0.46 °C per decade during 1979–2018 (REF.[38]) (Supplementary Fig. 1). Moreover, meteorological data obtained in the AWT region show large-scale warming[40,41].

The warming rate also shows pronounced seasonal and spatial differences[42,43]. The rate of winter warming (0.46 °C per decade) was almost double that of summer warming (0.26 °C per decade) during 1960–2013. This intense winter warming started in 1955 (REFS[38,44,45]), whereas summer warming began after 1986 (REF.[36]). The warming is spatially non-uniform. The warming rate increases not only from south to north[37,41,46–48] (Supplementary Fig. 2) but also with elevation; the highest warming rate (0.25 °C per decade) was observed above ~3,500 m during 1961–1990 based on data from 165 meteorological stations[49]. However, reported values for the warming rate at very high elevations are controversial owing to sparse data coverage above 4,500 m[50–52]. The observed elevation-dependent warming is mainly attributed to snow–albedo and ice–albedo feedback, whereby the loss of highly reflective snow and ice cover increases the amount of solar energy absorbed, leading to more warming[50]. Other factors, such as changes in cloud cover[53,54], atmospheric water vapour content[51], vegetation growth[55] and stratospheric ozone[56], have also been suggested as possible drivers.

Altered precipitation patterns. The ensemble means of seven state-of-the-art gridded precipitation products (three station-based and four atmospheric reanalysis data sets) indicate a slight overall increase in annual precipitation over the AWT from 1980 to 2018 (3.4 ± 2.8 mm per decade; $P = 0.3$) (FIG. 1a). This statistically non-significant precipitation change results from the averaging-out of substantial but spatially heterogeneous changes, specifically a north–south dipole pattern in precipitation trends[5]. Substantial precipitation increases have been observed in both the endorheic basins (11.0 ± 9.7 mm per decade, $P < 0.01$) of the northern AWT and the exorheic basins of the northern AWT, including the Salween, Mekong, Yangtze and Yellow River basins (12.3 ± 6.8 mm per decade, $P < 0.01$)[57,58]. By contrast, the exorheic basins of the southern AWT, including the Brahmaputra, Ganges and Indus River basins, exhibited a statistically significant decrease in annual precipitation (-26.1 ± 11.8 mm per decade, $P < 0.01$) over the same period[4,59] (FIG. 1b).

The seasonal variability of precipitation trends also differs from north to south, as has been shown in station-based observations as well as data reanalyses since 1979. The AWT generally experiences a wet summer and a dry winter, with 60–90% of precipitation occurring during June–September[46]. The current trends towards

Author addresses

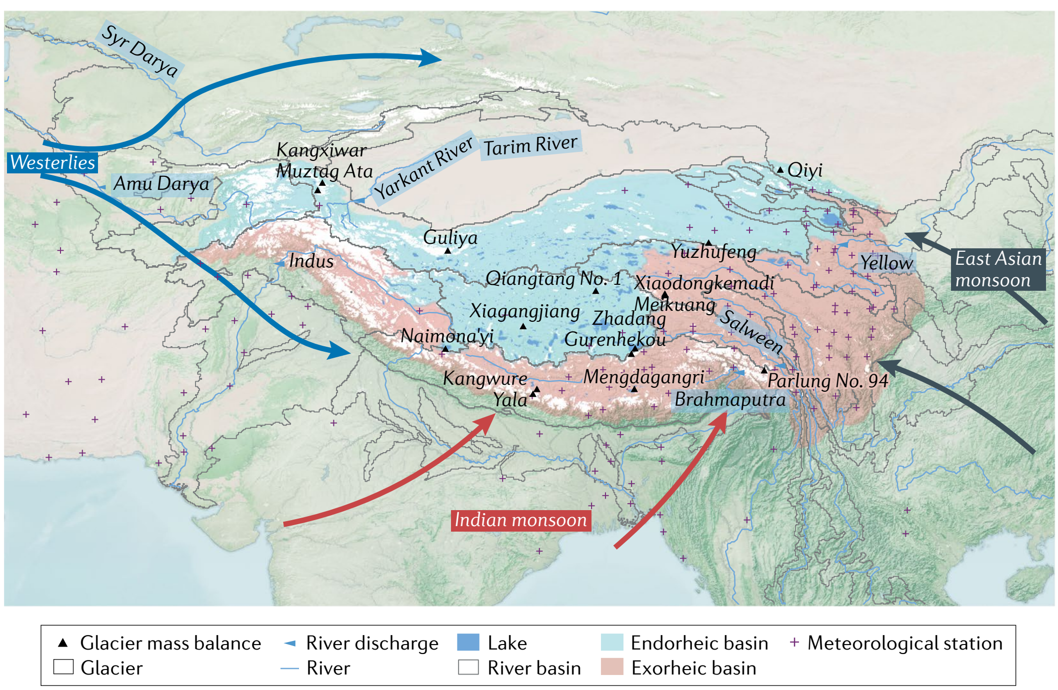
[1]State Key Laboratory of Tibetan Plateau Earth System, Resources and Environment, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China.
[2]School of Geography and Sustainable Development, University of St Andrews, St Andrews, UK.
[3]Department of Earth Sciences, University of Gothenburg, Gothenburg, Sweden.
[4]Faculty of Geosciences, Department of Physical Geography, Utrecht University, Utrecht, The Netherlands.
[5]Sino-French Institute for Earth System Science, College of Urban and Environmental Sciences, Peking University, Beijing, China.
[6]Byrd Polar and Climate Research Center, The Ohio State University, Columbus, OH, USA.
[7]International Institute for Applied Systems Analysis, Laxenburg, Austria.
[8]State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing, China.

Box 1 | The Asian water tower

The Asian water tower (AWT) covers an area of ~3×10^6 km^2 and comprises abundant solid and liquid freshwater reservoirs. Solid water reservoirs exist in the form of seasonal snow cover[164], subsurface ice in permafrost environments (which covers an area of ~1,480,000 km^2)[165] and more than 77,000 glaciers (which have a total area of about 83,350 km^2)[166], the largest glacierized area outside the Arctic and Antarctic[166]. Glacier meltwater is the primary source of the headwaters of Asia's 13 major river systems (total annual run-off 656 ± 23 Gt[20]) and the source of 1,424 lakes larger than 1 km^2 (which had a total area of 50,323 km^2 in 2018 (REF.[85])). These lakes provide important reservoirs for regions that experience periodic drought stress[107]. Rapid melting of these glaciers can also cause hydrological disasters, including glacier lake outburst floods[167,168] and glacier ice collapses[32,169].

Hydrologically, the AWT can be divided into endorheic basins (closed lakes and internally inflowing rivers) (see the figure, blue), located mostly in the central and northern sectors, and exorheic basins (outflowing rivers) (see the figure, red), located mainly in the south (unpublished work). Endorheic basins represent 46% of the AWT area and include 44% of its glaciers, whereas exorheic basins cover the remaining 54% of its area and 56% of its glaciers (see the figure). Both basin types exhibit distinctive patterns in the distribution of aqueous components (atmospheric water vapour, precipitation, river run-off, glaciers and lakes). Exorheic basins are characterized by high annual precipitation (866 ± 237 mm) and river run-off (80% of the total[20]). Although endorheic basins are characterized by lower annual precipitation (311 ± 86 mm)[170] and river run-off (~20% of the total), they make up ~73% of the lakes included in the AWT (as of 2019, 1,087 lakes with a total area of 45,466 km^2). In the figure, locations of meteorological stations outside China are from REF.[59].

The large-scale atmospheric circulation is one of the main drivers of hydrological changes in the AWT, in addition to global warming. Atmospheric reanalysis and in situ data demonstrate that seasonal shifts in the Indian monsoon and westerlies[171] are the primary mechanism shaping the spatio-temporal distribution of atmospheric water vapour and precipitation over the AWT[62,172], which together contribute ~77% of the region's total precipitation[173], with the remainder contributed by the East Asian monsoon (see the figure). The prevailing mid-latitude westerlies in the mid-upper troposphere[171] carry moisture from the Mediterranean–Iranian Plateau via local evapotranspiration. The westerlies also modulate the strength of moisture flow and precipitation in spring and early summer via dynamic interaction with the Indian monsoon[70,71]; thermal differences between the AWT and tropical oceans in spring and summer drive the strength of the Indian monsoon[174] and also force the westerlies to retreat northwards. The Indian monsoon transports moisture from tropical oceans[68] northwards across the Indian subcontinent, providing copious precipitation in southern and central parts of the AWT, which is modulated by the El Nino/Southern Oscillation[65]. These processes (relative to moisture transport by the westerlies and Indian monsoon) affect the surface energy budget, which, in turn, changes temperature and melting patterns in the AWT.



increased precipitation in the spring and winter were established in the eastern and central Tibetan Plateau during 1961–2007, alongside trends towards decreasing precipitation in winter in the south-eastern Tibetan Plateau[60,61]. This dipole pattern of precipitation change is probably caused by shifts in the two large-scale circulation systems that dominate the AWT: the westerlies and the Indian monsoon[62,63]. Indeed, dynamic forcing from these systems is the predominant contributor to precipitation changes in the AWT, whereas thermodynamic processes[20,64,65] (the other main contributor) produce a largely homogeneous response according to Clausius–Clapeyron scaling. In particular, the Indian monsoon has exhibited a weakening trend since the 1980s (−5.4% per decade, $P = 0.01$)[5,66,67]. A weaker Indian monsoon entrains less moisture from tropical oceans across the Indian

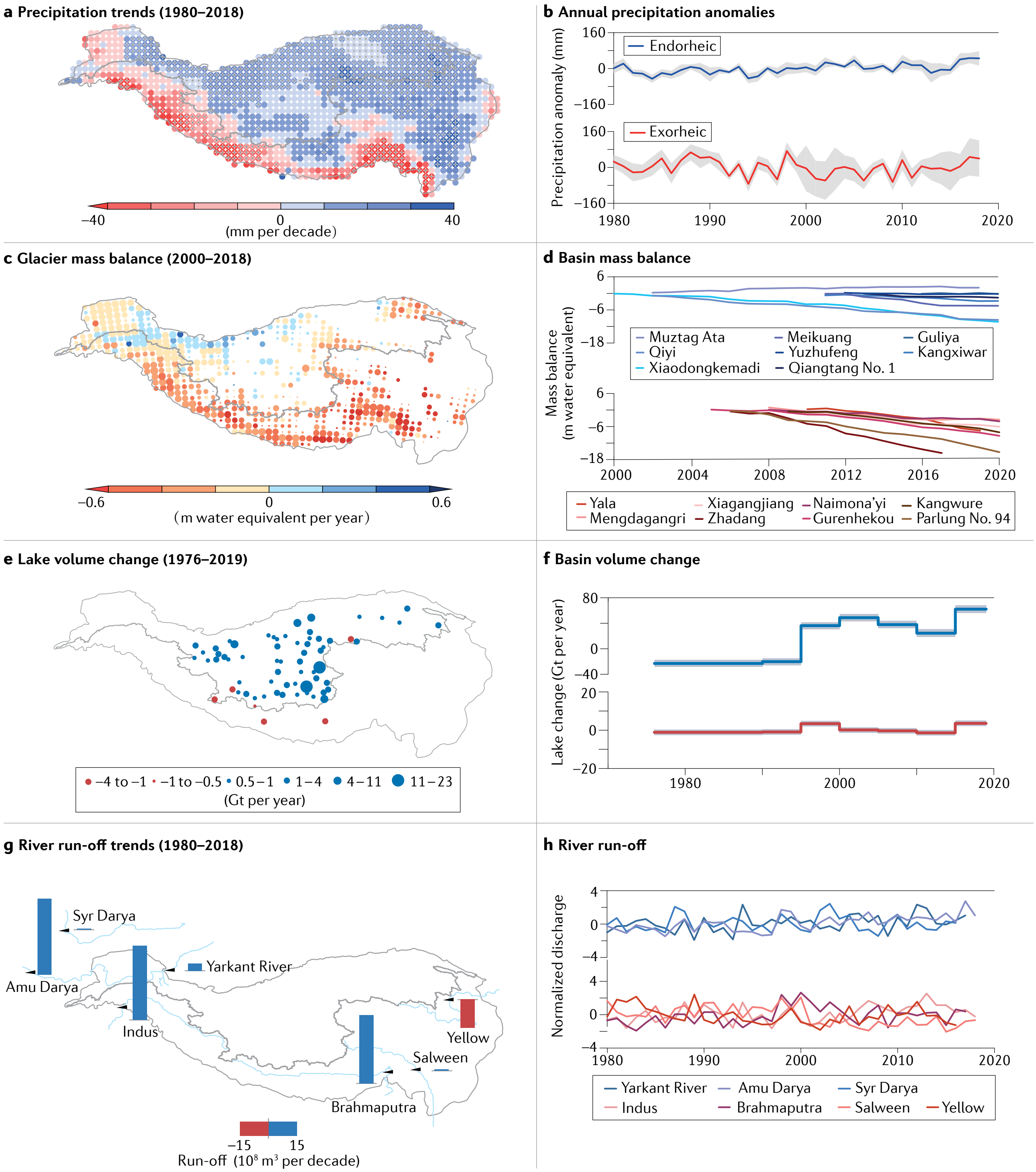


Fig. 1 | **Synthesis of observed changes in different components of the Asian water tower. a** | Spatial distribution of precipitation trends from 1980 to 2018 using ensemble mean values for annual precipitation derived from observational data sets (Climate Research Unit (CRU), Global Precipitation Climatology Centre (GPCC) and Global Precipitation Climatology Project (GPCP)) and reanalysis products (National Centers for Environmental Prediction (NCEP), Fifth Generation European Centre for Medium-Range Weather Forecasts Reanalysis (ERA5), Japanese 55-year Reanalysis (JRA55) and Indian Monsoon Data Assimilation and Analysis (IMDAA)). **b** | Time series of ensemble mean values for annual precipitation anomalies in endorheic and exorheic basins, calculated by comparison with a historical reference period (1971–2000). **c** | Spatial patterns of glacier mass balance between 2000 and 2018 based on digital elevation models[75]. **d** | Eight continuous mass balance measurements in endorheic and exorheic basins. **e** | Spatial pattern of basin-wide lake volume changes between 1976 and 2019 (REF.[94]). **f** | Time series of total lake volume changes in endorheic and exorheic basins. **g** | Spatial pattern of run-off trends for seven large rivers. **h** | Time series of run-off for three rivers in endorheic basins and four rivers in exorheic basins.

subcontinent[68], resulting in decreasing precipitation in the southern AWT where precipitation is primarily dominated by upslope moisture transport over the Himalayas or mid-tropospheric moisture corridors[69]. By contrast, the strengthening of prevailing mid-latitude westerlies[5] has increased moisture transport into the northern and western AWT, especially in spring and summer[70,71]. This intertwined competition between the two large-scale circulations has shaped the distinct north–south dipole pattern of precipitation changes over the AWT.

Glaciers. Owing to the dominant role of warming in controlling glacier mass balance, most glaciers on the AWT have experienced retreat of their termini and negative mass balance anomalies in the past two decades (REFS[5,72,73]). Geodetic measurements from several digital elevation model comparisons reveal an accelerating rate of glacier mass loss (−16.3 ± 3.5 Gt per year during 2000–2016 (REF.[74]), −19.0 ± 2.5 Gt per year during 2000–2018 (REF.[75]) and −21.1 ± 4.8 Gt per year during 2000–2019 (REF.[76])) across the whole AWT. On the basis of the calculated annual rate of glacier mass loss of −19.0 ± 2.5 Gt per year[75], the total glacier mass loss across the whole AWT during 2000–2018 is about 340 Gt. This mass loss and reductions of gravitational driving stress have reduced glacier velocity during 2000–2017, with the largest deceleration seen for glaciers in the Nyainqentanglha Mountains (−37.5 ± 1.1% per decade)[77].

Divergent regional precipitation trends (that is, the north–south dipole pattern already described) contribute to heterogeneous rates of glacier melting[5,74–76,78–80] (FIG. 1c). Particularly substantial losses of ice mass are evident for glaciers in the monsoon-influenced Himalayan ranges and south-eastern AWT[5,72], where reductions in precipitation have also been observed. Several large-scale geodetic studies also provide evidence that the largest negative mass balances in the AWT are concentrated in the eastern Nyainqentanglha Mountains (−0.55 m water equivalent per year during 2000–2018)[74–76].

However, in regions dominated by the westerlies (such as the Karakoram, eastern Pamir and western Kunlun), where precipitation has increased[81], geodetic studies have revealed that glaciers typically remained stable or even expanded in size and volume (0.04 ± 0.04 m water equivalent per year during 2000–2018)[74–76,80,81]. Ground-based mass balance observations on benchmark glaciers, despite being based on different numbers of glaciers (and, therefore, returning different values), also support such a spatially heterogeneous pattern. In the monsoon-dominated exorheic basins, glacier mass loss averaged −0.72 m water equivalent per year during a period from the early 2000s to 2020 for eight representative glaciers, in contrast to a reduced mass loss of −0.23 m water equivalent per year for eight representative glaciers in the westerlies-dominated endorheic basins (FIG. 1d). Muztagata No. 15 Glacier in the eastern Pamirs, for example, exhibited a slight mass gain (mean 0.12 m water equivalent per year) during the early 2000s to 2020 (FIG. 1d). Nevertheless, marked variability still exists within these regions, as revealed by a slight mass loss of the westerlies-dominated Guliya Glacier in the western Kunlun Mountains (FIG. 1d). However, the most recent data from 2015–2020 for these regions suggest that the 'Karakoram Anomaly' has come to an end, meaning that glacier mass loss is now prevalent even in these regions, mainly driven by an increase in summer temperatures[76,80].

Lakes. As with glaciers, divergent changes in the strength of the westerlies and the Indian monsoon have driven corresponding changes in alpine lakes located in the endorheic and exorheic basins of the AWT[82–84] (FIG. 1e).

Satellite-based lake mapping indicates that the number of lakes with areas >1 km^2 increased from 1,080 in 1976 to 1,424 in 2018, and that the total lake area increased from 40,124 km^2 to 50,323 km^2 over the same time period[85]. Increased precipitation, which might be associated with a positive phase of the Atlantic Multidecadal Oscillation since the mid-1990s (REF.[58]), was the major contributor (>70%) to an overall expansion of lake area from the 1970s to 2015 (REFS[86–89]). The expanded lake area can alter lake evaporation and further influence water balance[90].

Overall, 77% of these expanded lakes occurred in endorheic basins, which accounted for 98% of the total increase in lake volumes[11,89,91–93] from 1976 to 2019 (~166 Gt of ~170 Gt)[94] (FIG. 1f). Among lakes in the AWT, Selin Co showed the largest water volume increase during 1976–2019 with a water mass gain of ~23 Gt[92,94,95] (FIG. 1e). These changes can, to a large extent, be attributed to increased summer precipitation in the endorheic basins[96], and represent the dominant gain in terrestrial water storage recorded by the Gravity Recovery and Climate Experiment (GRACE)[97,98]. The exorheic basins, by contrast, account for only a minor fraction of expanded lakes (23%) and lake volume increases (2%) across the AWT, and some larger lakes (such as Yamzho Yumco, Paiku Co, Mapam Yumco and La'nga Co) are shrinking by a small amount (up to −5 Gt)[83,85]. The lake volume changes in exorheic basins are accounted for by decreased summer precipitation[96].

Rivers. Changes in precipitation, glacier mass and snow melt, permafrost thawing and the increase in active layer depth, alterations in lake and underground water storage, together with changes in other hydrological variables (such as warming-induced increases in evapotranspiration) could all lead to changes in surface run-off, through which the AWT supplies water to downstream areas. For ten major rivers originating from the AWT[20], historical annual run-off at mountain outlets (that is, locations where rivers leave the mountains and enter the plains) has demonstrated widespread changes over 1980–2018, with statistically significant increases in run-off in four rivers, non-significant decreases in two rivers and largely unchanged run-off in the remaining four rivers. This heterogeneity again reflects differences between the exorheic and endorheic basins[99–103] (FIG. 1g).

During 1980–2018, annual river run-off across most of the AWT showed a significant increase in rivers such as the upper Indus (+3.9 Gt per decade) but stable status in rivers (such as the Yangtze and Salween) that are most affected by the westerlies or receive considerable contributions from glacier melt (FIG. 1h). However, a decline in run-off was observed in the Yellow River

(−1.5 Gt per decade) over the same time period, probably owing to the weakening summer monsoon[2,5] (FIG. 1h) and simultaneous increase of evapotranspiration, among other factors[4,104,105].

For the endorheic rivers located in arid and semi-arid regions in the northern and western AWT, where the climate is typically continental, glacier melt is the primary source of surface run-off. Along with increased convective precipitation in the Tibetan Plateau interior region[4], these endorheic rivers also experience intensified glacier and snow melt as well as degradation of frozen ground caused by atmospheric warming[3]. These changes have led to increased total amounts of river run-off in the past four decades. For example, the observed annual run-off of the Tarim River showed a significant upward trend of +0.9 Gt per year for its three major tributaries, Yarkant River (mainly draining the eastern Pamir and northern Karakoram), Hotan River (western Kunlun Shan) and Akesu River (central Tien Shan).

AWT imbalance. These changes collectively indicate a state of imbalance in the AWT. Specifically, the loss of ice mass accompanied by lake water gain and increasing or stable run-off for most rivers suggest an increasing disequilibrium between solid (snow and glaciers) and liquid (lakes and rivers) reservoir components accrued since the 1980s. This imbalance is clearly demonstrated by contrasts between the northern endorheic and southern exorheic basins, which reveal a spatial redistribution of resources: relative to each other, the northern endorheic basins generally exhibit lower losses of solid water losses but large gains in liquid water, whereas southern exorheic basins exhibit substantial losses of solid water and smaller gains in liquid water. These divergent spatial patterns of changes in the AWT are primarily driven by north–south dipole variations in precipitation arising from strengthening westerlies and a weakening Indian monsoon[5] as well as rapid atmospheric warming. These warming and circulation changes have resulted in an imbalance in the status of surface run-off, characterized by evidence of an increasing trend in westerlies-dominated basins and a slightly decreasing trend in the monsoon-dominated basins (FIG. 1h).

It is also noteworthy that the changes in key hydrology and glaciology components of this AWT imbalance are interconnected, which could further contribute to differences between the endorheic and exorheic basins. For example, glacier melting (driven by warming) is an important source of many AWT lakes and rivers. The contribution of glacial meltwater to changes in lake water storage and river run-off is more important in the endorheic basins than in the exorheic basins. For the exorheic basins of the southern AWT, however, the increase in glacier meltwater supply[5,106,107] does not compensate for the decline in monsoon precipitation, thereby resulting in reduced river run-off in these basins (FIG. 1).

Future projections

Warming and changes in precipitation regimes are expected to persist into the future according to the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project Phase 5 (CMIP5)[3]. Therefore, currently observed trends in hydrological cycling and changes in the water balance of the AWT are also likely to continue in coming decades. Accordingly, model projections of the future of the AWT have an important bearing on building a strong knowledge base for decision makers to prepare for climate change. In the next sections, we discuss projections of the dynamics of atmospheric vapour transport (precipitation), which result in increases in liquid water (glacier melt, river run-off and lakes), and the implications of these changes for the imbalance of the AWT under different emission and socio-economic pathway (SSP) scenarios.

Ubiquitous precipitation increase. Precipitation is anticipated to increase in a warming world[3]. The ensemble means of earth system models archived in the CMIP5 show that annual precipitation of the AWT will increase during 2070–2099 by 6.7 ± 5.0%, 8.9 ± 5.6% and 13.5 ± 8.9% under the low (representative concentration pathway (RCP) 2.6), medium (RCP4.5) and high (RCP8.5) emission scenarios, respectively, relative to the historical period 1970–2000 (REF.[108]). Similar increases are projected in the CMIP6, with an increase of 8.6 ± 5.1%, 10.9 ± 6.4% and 21.7 ± 10.7% under shared SSP126, SSP245 and SSP585 scenarios, respectively (Supplementary Fig. 3). It is important to note that all models predict an increase in precipitation over the whole AWT[26], including in the southern AWT, which diverges from observations over the past 40 years[5] that show a decreasing regional trend. The projected future revival of precipitation in the southern AWT is linked to an intensification of Indian summer monsoon rainfall in a warming world, along with a decrease in anthropogenic aerosol emissions[66,109–111]. However, this precipitation increase shows strong spatial variations that are twice as large over the endorheic basins as over the exorheic basins (FIG. 2a,b). This difference in precipitation change in endorheic versus exorheic basins is likely to be a result of circulation system changes over the AWT[112,113]. The predicted overall increase in precipitation across the AWT can also be found in other northern hemisphere locations (Supplementary Fig. 4).

Nonetheless, it is worth keeping in mind that projections of precipitation are subject to considerable uncertainty. Projected precipitation changes during 2070–2099 (relative to 1970–2000) among different models vary from 0.8% to 16.5% under RCP2.6, from 0.1% to 26.5% under RCP4.5 and from 2.0% to 47.7% under RCP8.5. The large uncertainties in these model projections arise partly from the poor representation of atmospheric dynamics in earth system models, related to a lack of appreciation of the contribution of atmospheric dynamics to the control of historical AWT precipitation[26], poor representation of convective-scale physical processes[114] and the effects of rugged and complex topography on moisture flux changes[115].

Accelerated glacier melting. Climate models show that the rate of warming over the glacierized area of the AWT is much higher than the global average and that glacier melting in the AWT is likely to accelerate further. More than one third of the ice mass and glacierized area of the

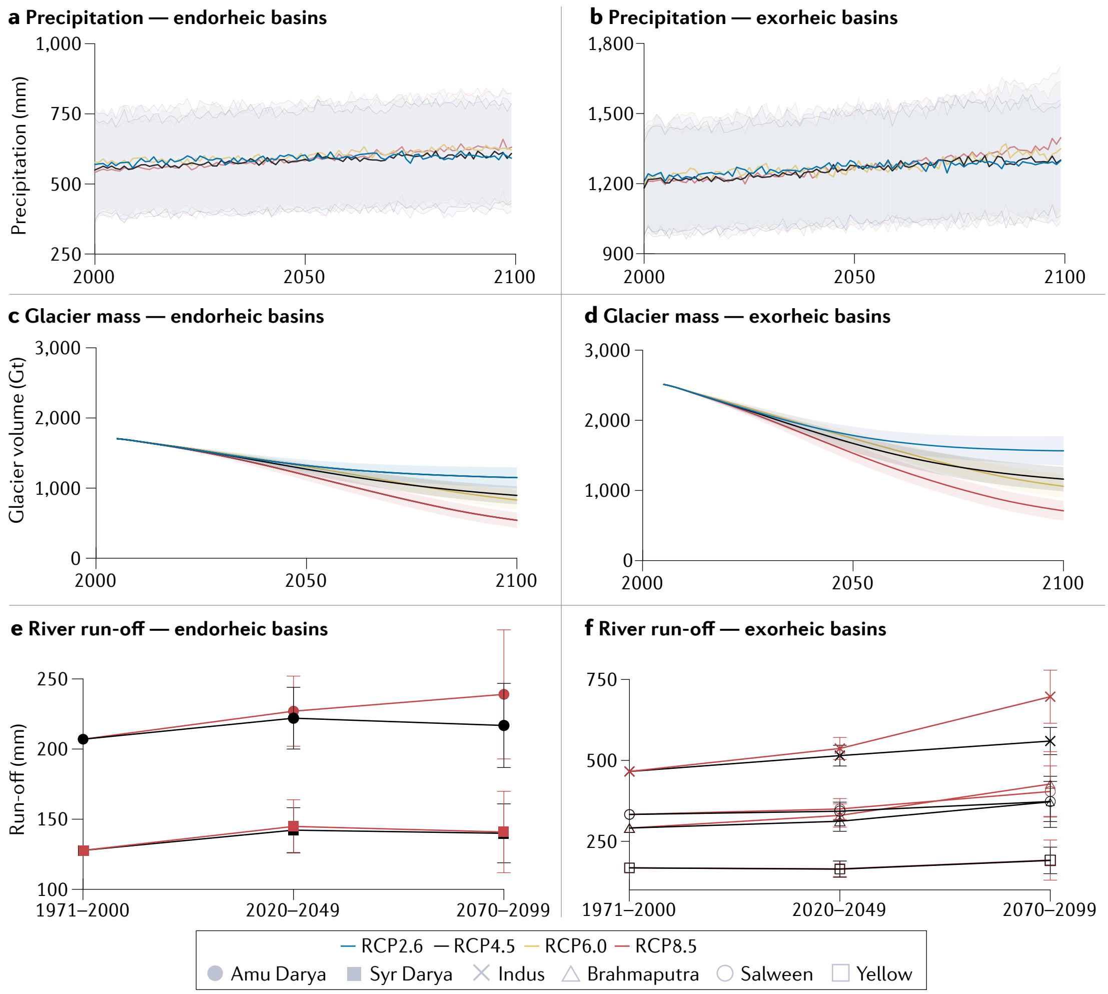


Fig. 2 | **Projected changes in precipitation, glaciers and river run-off in the Asian water tower. a,b** | World Climate Research Programme (WCRP) Coupled Model Intercomparison Project Phase 5 (CMIP5) projections of precipitation changes from 2000 to 2100 in endorheic basins (part **a**) and exorheic basins (part **b**) of the Asian water tower (AWT) under RCP2.6, RCP4.5, RCP6.0 and RCP8.5 scenarios. **c,d** | CMIP5 projections of glacier mass loss in endorheic basins (part **c**) and exorheic basins (part **d**) from 2000 to 2100 under RCP2.6, RCP4.5, RCP6.0 and RCP8.5 scenarios[116]. **e,f** | CMIP5 projections of river run-off in two large rivers with endorheic basins (part **e**) and four large rivers with exorheic basins (part **f**) for the near future (2020–2049) and far future (2070–2099) under RCP4.5 and RCP8.5 scenarios. RCP, representative concentration pathway.

AWT is projected to be lost by the end of this century even under the RCP2.6 scenario[116,117]. However, predictions of ice mass loss in different basins vary greatly under different scenarios. For example, the rate of glacier loss is significantly higher under the RCP4.5 (49 ± 7%) and RCP8.5 (64 ± 5%) scenarios[116]. Other studies report similar results; that is, losses of ice mass reaching 67 ± 10% under RCP8.5 by the end of this century[118].

In the endorheic basins of the AWT, ice mass loss is projected to be 32.5 ± 8.7%, 47.5 ± 7.6%, 51.3 ± 8.1% and 68.2 ± 6.5% under the RCP2.6, RCP4.5, RCP6.0 and RCP8.5 scenarios, respectively; in the exorheic basins of the AWT, the projected ice mass loss is 37.7 ± 8.4%, 53.8 ± 6.9%, 57.8 ± 6.7% and 71.8 ± 5.6% under these same scenarios (FIG. 2c,d). Even without continuous warming, more than 20% of the volume of ice in the AWT is projected to be lost by 2100 (REFS[78,119]).

Considerable spatial variation for the projected ice mass loss over the AWT is driven by the spatial variability of the complex interactions between warming and changes in the two large-scale atmospheric circulation systems. However, by 2100, glaciers in monsoon-dominated regions (such as the Himalayas and the Hengduan Mountains) could lose more than half of their present-day ice mass (75–78% under a RCP4.5 scenario). By contrast, glaciers in westerlies-dominated regions (Pamir, Karakoram and West Kunlun) could lose about 33–52% of their present-day ice mass under the RCP4.5 scenario (REF.[116]), because precipitation in the westerlies-dominated regions occurs as non-monsoonal winter snowfall, which could partly offset warming-induced glacier loss[120].

Continued lake expansion. Although current understanding of changes in alpine lakes is limited[3] and development of more sophisticated models is needed to improve future projections of lake water storage over the AWT, some qualitative and even semi-quantitative predictions are possible. A lake mass balance model simulation suggests that the average lake level in the

Qiangtang region could rise by ~2 m from 2020 to 2035 (REF.[121]) (Supplementary Fig. 5). The water gain through lake expansion could be as large as 1,000 Gt by 2100. However, this model did not consider future cryosphere melt and warming-induced changes in lake evaporation[90,121], both of which were important contributors to historical lake expansion in this region[98,122] and could continue to be so in the future. However, we can reasonably expect that lakes in the endorheic basins of the AWT could experience continuous expansion up to 2100 on the basis of projected future changes in moisture flux[115].

Increased river run-off. Cryospheric–hydrological modelling of hypothetical climatic conditions or climate model projections is commonly used for assessing changes in river run-off. On the basis of 22 bias-corrected and downscaled general circulation model ensemble means[123], run-off in the headwater basins of the AWT is expected to increase continuously up to 2100 in response to future warming under both the RCP8.5 and RCP4.5 scenarios. Relative to 1971–2000, run-off projections for 2070–2099 showed substantial increases for the exorheic basins: 49 ± 17% and 20 ± 9% for the Indus, 47 ± 33% and 28 ± 26% for the Brahmaputra, 27 ± 24% and 16 ± 19% for the Salween and 16 ± 36% and 15 ± 24% for the Yellow Rivers, respectively[19,123–126]. By contrast, run-off projections for the endorheic basins showed only slight increases: 10 ± 23% and 9 ± 16% for the Syr Darya and 15 ± 22% and 5 ± 14% for the Amu Darya Rivers under the RCP8.5 and RCP4.5 scenarios, respectively (FIG. 2e,f).

Precipitation increase associated with changes in the westerlies and monsoon circulations is a major driver of future surface run-off increases across the AWT (FIG. 2a,b). Continued warming and interactions between the westerlies and monsoon circulation systems are predicted to create more intensive water cycling in both exorheic and endorheic basins[2,19,63,123,124]. However, uncertainties also exist in future projections of run-off, and different studies can even report opposite results. For example, an increase in run-off has been projected for the upper Indus River basin by 2100 under RCP4.5 and RCP8.5 (49–51%)[125], in contrast to a decrease (–15 to –17%) under future dry scenarios[124]. Similarly, different studies have reported varying determinations of the trend in future run-off in the Tarim River basin under the RCP2.6, RCP4.5 and RCP8.5 scenarios[124,127,128]. Further studies are needed to narrow down the uncertainties in run-off projections in the AWT, because these projections inform assessments of future freshwater supplies for millions of people living upstream and downstream. Proactive measures should be taken to strengthen confidence in these projections by improving the validity and resolution of general circulation models, or by making additional physical constraints and corrections of future climate projections developed by the Intergovernmental Panel on Climate Change[19,27,118,129].

Persistent imbalance of the AWT. The currently observed imbalance of the AWT is expected to continue or even be exacerbated under future climate change. Glacier mass loss over the AWT could be 64 ± 5% by 2100 under the RCP8.5 scenario[116]. Run-off in the Indian monsoon-dominant region (such as in the Indus, Brahmaputra, Salween and Yellow River basins) is projected to significantly increase, whereas run-off in the westerlies-dominant region (such as in the Syr Darya and Amu Darya River basins) is projected to slightly increase or remain stable.

The exacerbating imbalance of the AWT might be driven primarily by more intensive evapotranspiration, which is caused by warming and greening of the endorheic basins and intensive glacier melting combined with increased Indian monsoon precipitation in the exorheic basins. Whether the observed contrast between endorheic and exorheic basins in lake changes will persist in the future remains uncertain, because few such projections exist for lakes at the moment. Past lake expansions in the endorheic basins of the AWT have been predominantly attributed to increased precipitation, with the contribution of glacier melting being considered of lesser importance. However, in the future, the contributions of glacier melting and permafrost thawing to surface run-off are projected to be increasingly important[118,130]. Although some preliminary studies have addressed permafrost degradation[131–134], they were insufficient to summarize the contribution of this process to lake expansion or run-off.

The changing connection between glaciology and hydrology with warming will further contribute to divergent hydrological responses between the endorheic and exorheic basins of the AWT. Under the RCP4.5 scenario, annual glacier run-off in all glacier-fed rivers of the AWT (except the Indus River[118]) is projected to reach a maximum in the middle of this century and to decline thereafter[118,135]. However, these changes can also influence run-off in endorheic rivers, such as the Amu Darya River, which is highly dependent upon glacier melt[136,137].

In summary, warming will accelerate glacier melting and shift the water resources (especially in eastern and south-western regions) of the AWT towards a liquid water-dominant state, particularly under high-emission scenarios. With increasing precipitation, overall water resources in the AWT are also expected to increase, and this increase might be even greater in exorheic basins than in endorheic basins, resulting in an exacerbation of its present imbalanced state. In turn, this imbalance between solid and liquid water states will reshape future water availability for downstream societies.

Projected changes in water resources

The consequences of increased total run-off from the AWT are influenced by water demand in downstream territories, which is driven by population growth and socio-economic development[138]. We now discuss the potential changes arising from these factors under the SSP2–RCP6.0 scenario (Supplementary Fig. 6).

Increasing water demand. At present, demand for water resources varies by orders of magnitude across regions downstream of the AWT, with the highest demand in the Indus basin (~299 Gt per year) and the lowest in the Salween basin (~5.1 Gt per year)[139]. This pattern is consistent with the fact that the Indus and Ganges-Brahmaputra River basins are densely populated and contain the world's largest irrigated agricultural area[140–142]. Furthermore, across all basins and among different water sectors, irrigation accounts for more than 90% of water use.

The total water demand across all basins is anticipated to increase by 11% by the 2050s and 18% by the 2090s. Projected demands for household use (4–9%) and irrigation (5–8%) are greater than those for industrial purposes (2%). Irrigation demand will remain at its highest levels throughout the 2050s–2090s. As the irrigated area and irrigation efficiency have remained constant since 2005 (REF.[138]), the projected increase in irrigation water demand is mainly attributed to climate change. The fact that percentage increases in household and industrial demands are comparable with those for irrigation demand suggests that climate change has almost equal importance to socio-economic changes in determining future water requirements downstream of the AWT.

The overall increase in water demand and the contributions of each water sector to the total increase all show large variations across basins. By the 2050s, total water demand will be derived largely from increased usage in the exorheic basins of the AWT (7.6–17.2%), with smaller increases in the endorheic basins, including the Amu Darya (5.0%) and Tarim (3.5%) Rivers (FIG. 3). By 2100, increased irrigation needs will dominate the total water demand in the Yangtze and Yellow River basins. By contrast, increases in irrigation and household use are projected to play almost equal roles in increased water demand in the Indus and Ganges-Brahmaputra River basins. The decline in groundwater storage in India, especially in the north-western region, has been exacerbated by its extraction for irrigation[143]. Increased irrigation and household water use in the Indus River basin can be attributed primarily to future projections of a rapidly growing population, although this is not the case in the Yangtze and Yellow River basins owing to a declining population.

Divergent changes in water stress. Regions downstream of AWT are currently experiencing medium to high levels of water stress, although large inter-basin variations exist[1]. The Indus, Tarim and Amu Darya River basins have high baseline levels of water stress, and satisfying their present-day water demands typically requires additional supplies from inter-basin water transfers or groundwater extraction. By contrast, the Yangtze, Yellow, Salween and Mekong River basins have a relatively low level of water stress. Overall, however, water stress across the AWT will not be alleviated under SSP2–RCP6.0 because projected increases in total run-off in upstream regions (~82 Gt per year) are not sufficient to meet the increases in total water demand in upstream and downstream regions combined (~178 Gt per year) (FIG. 4, top; see Supplementary Fig. 7).

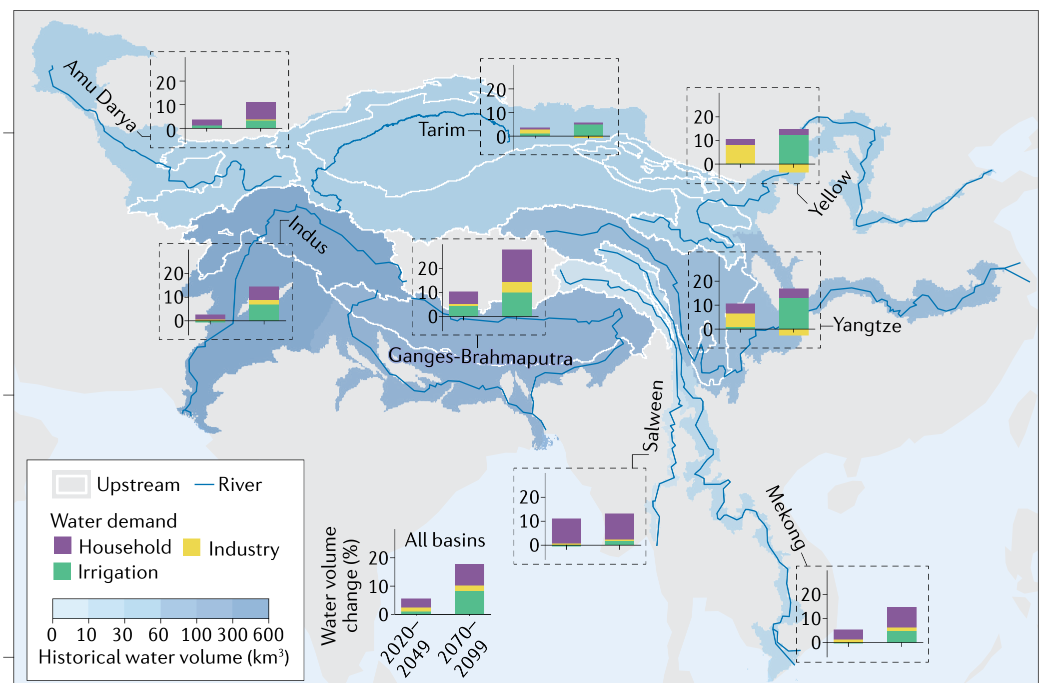


Fig. 3 | **Projected changes in anthropogenic water resource demand in the Asian water tower.** Projected changes in water demand for endorheic basins (light blue; Amu Darya and Tarim), exorheic basins (dark blue; Indus, Ganges-Brahmaputra, Salween, Mekong, Yellow and Yangtze) of the Asian water tower (AWT)[1] in the near future (2020–2049) and far future (2070–2099) relative to 2006–2015. Stacked bars show relative changes in water withdrawal for agricultural (green), domestic (purple) and industrial (yellow) purposes. These projections are based on calculations using the H08 global hydrological model under SSP2–RCP6.0 conditions[138] performed by the Water Futures and Solutions (WFaS) initiative. Grey areas represent regions not hydrologically connected to rivers flowing out of the AWT. RCP6.0, moderate-emission representative concentration pathway scenario; SSP2, middle-of-the-road narrative of the shared socio-economic pathway.

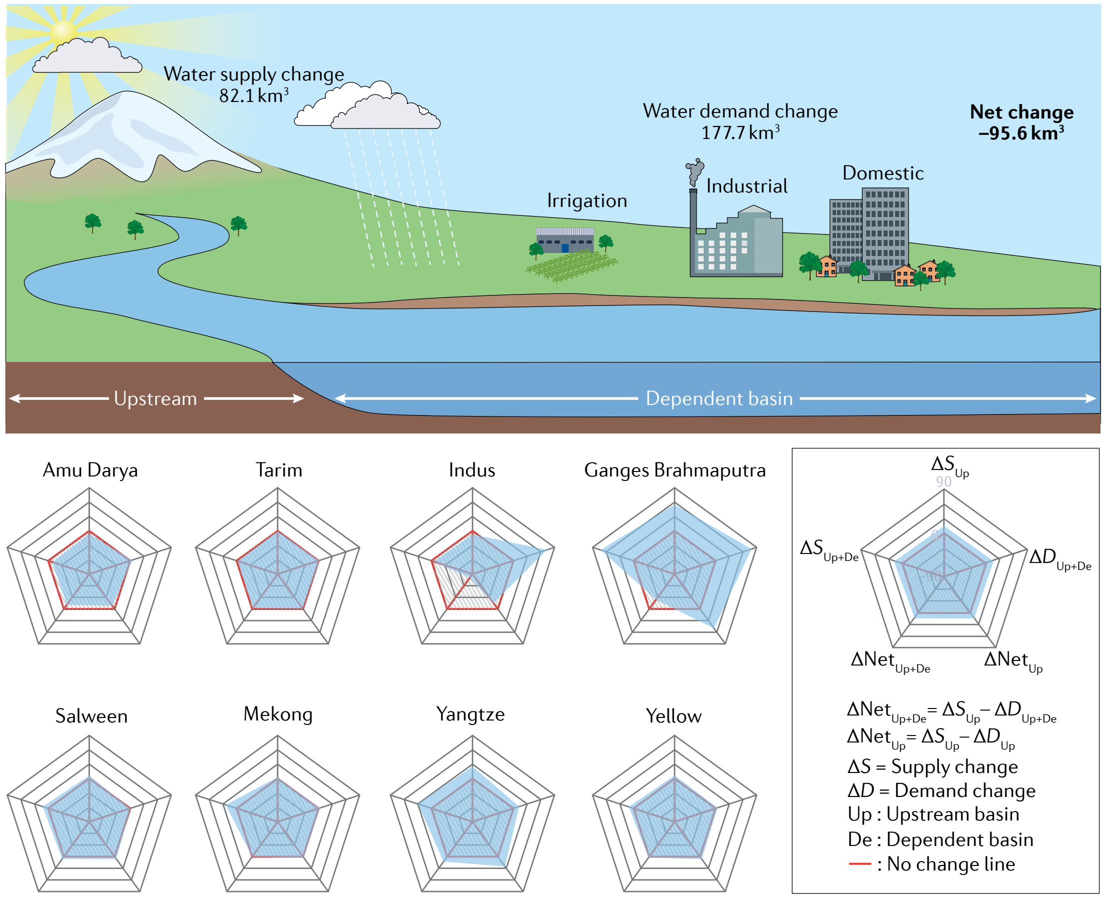


Fig. 4 | **Projected changes in water resources for the Asian water tower and its downstream dependent areas.** Top: Projected changes in upstream water supply and downstream water demand in Asian water tower (AWT) and dependent regions, and the net difference between these projections, between 2080–2099 and 2006–2015. Bottom: Projected changes in water supply and water demand, and the net difference between these projections, between 2080–2099 and 2006–2015 for two endorheic basins (Amu Darya and Tarim) and six exorheic basins (Indus, Ganges-Brahmaputra, Salween, Mekong, Yellow and Yangtze). Water supply data taken from World Climate Research Programme (WCRP) Coupled Model Intercomparison Project Phase 5 (CMIP5) RCP6.0 model projections. Water demand data taken from the Water Futures and Solutions (WFaS) initiative SSP2–RCP6.0. ΔNet_{up}, difference between projected changes in water supply and water demand over the AWT; ΔNet_{De}, difference between projected changes in water supply from the AWT and changes in water demand from both the AWT and its downstream dependent areas; RCP6.0, moderate-emission representative concentration pathway scenario; SSP2, middle-of-the-road narrative of the shared socio-economic pathway.

Divergent changes are apparent in water stress conditions across basins. In the upper reaches of the Indus River, the already high baseline water stress will be worsened by 2100. This worsening of water stress is linked to a minor decline in upstream run-off (about −5 Gt per year) and a large increase in total water demand (~74 Gt per year) (FIG. 4, bottom). Thus, the increased water stress will not be buffered even if additional water supplies from downstream sources (instead of groundwater extraction and inter-basin water transfer) are included (FIG. 4, bottom). Similarly, for the Ganges-Brahmaputra River basin, the already relatively high level of water stress[1] will increase further because the upstream increase in surface run-off (~63 Gt per year) is insufficient to compensate for the increase in water demand from the upper region and its dependent downstream area combined (~82 Gt per year). By contrast, in the Yellow River basin, the projected small increase in upstream run-off (~8 Gt per year) is sufficient to meet or exceed the increase in total water demand (~4 Gt per year), which suggests that the present-day relatively high water stress conditions in this basin will be substantially alleviated. Divergent patterns of water stress between different basins of the AWT are also revealed when available water resources per capita are used to measure the level of water stress[26].

Water diplomacy. Most big rivers originating from the AWT are transboundary rivers shared by about ten countries. The imbalance of the AWT has already caused (and will continue to cause) serious political issues related to water use for all countries affected by these transboundary rivers. Water use policies downstream of the AWT typically affect at least 2–6 countries, including China, Pakistan, India, Thailand, Myanmar and Afghanistan, which are home to more than 805 million people.

Almost all transboundary rivers, except the Salween and Mekong Rivers, are projected to experience an increased severity of water stress under the SSP2–RCP6.0 scenario. The growing scarcity of water resources in these basins as well as diverse national interests and power asymmetries between these riparian countries are expected to have implications for the political and economic status quo in these countries, and to increase the attendant potential for dispute and conflict over shared water resources in the future. Indeed, some ongoing transboundary dialogues over these river basins have not all been successful in resolving water scarcity issues and conflicting views among countries. For example, the 1996 Ganges Treaty is an agreement between India and Bangladesh to share surface water at the Farakka Barrage in West Bengal, which lies within a few kilometres of the India–Bangladesh border. However, the 1996 agreement was simply based on the volumetric division of river flow at the border between these two countries and neglected to take a basin-wide approach to river management or to consider the effects of water use by upstream riparian countries (such as Nepal) on water resources at the Farakka Barrage. Similarly, the 1960 Indus Waters Treaty, which survived two violent conflicts between India and Pakistan and was hailed as a successful model of international water dialogue, only relates to the sharing of irrigation waters and does not consider not basin-level cooperation. Hydro-diplomacy is essential to bring countries and diverse stakeholders in these conflict-prone river basins together for increased dialogue and cooperation, and to seek basin-wide solutions rather than local-centric or national-centric solutions to transboundary water management[41,144,145].

Transboundary rivers originating from the AWT mainly affect developing countries in which water resources have an extremely uneven seasonal distribution, especially in monsoon-dominated basins. Current water infrastructure in these countries, including water storage and irrigation facilities, are often insufficient in monsoon-dominated basins, leading to flooding and underutilization of hydroelectric potential during the wet season and severe water shortages during the dry season[141,146]. Moreover, irrigation technologies and water use strategies, especially in the Indus, Ganges-Brahmaputra and Amu Darya River basins, are generally inefficient, resulting in high water demand per unit of product[140,147,148]. This situation calls for the countries relying on these transboundary rivers to cooperatively develop new, high-efficiency water usage strategies and technologies. Massive investment is urgently needed to build on and improve water infrastructure and to update water-saving measures in downstream countries.

Conclusions and future perspectives

This Review provides a comprehensive overview of changes in the AWT and their associated effects on downstream water resources from a perspective that integrates atmosphere, cryosphere, hydrosphere and human systems. Rapid warming, strengthening of mid-latitude westerlies and weakening of the Indian monsoon resulted in an imbalance of the cryosphere and hydrosphere during 2006–2015, characterized by reduced solid water in glaciers (−190 ± 25 Gt) and increased liquid water in lakes (61 ± 7 Gt) as well as a spatial imbalance in water resources characterized by increases in the endorheic basins and declines in the exorheic basins (FIG. 5). In a warming world, climate change will further exacerbate this imbalance between solid and liquid water states, resulting in a liquid water-dominant status of the AWT under the high-emission RCP8.5 scenario. Climate model projections indicate that the hydrological cycle will accelerate, and that the buffering role of the cryosphere will diminish. Relative to 1980–1990, annual mean precipitation in the AWT is projected to increase by 8.9 ± 5.6%, with higher increases in the exorheic basins (11.7 ± 7.6%) than in endorheic basins (8.1 ± 5.4%). Glacier mass is projected to decrease by 51.2 ± 7.2%, with a higher decline seen in exorheic basins (53.8 ± 6.9%) than in endorheic basins (47.5 ± 7.6%) by 2100 under the RCP4.5 scenario. The total water supply to the AWT is projected to increase by 2100, but exorheic basins will see a greater increase in supply than endorheic basins under the RCP4.5 scenario. However, with the diminishing buffering effect of the cryosphere, the seasonality of surface run-off is projected to change; more glacier meltwater will be released in early spring but run-off will decline in the summer months. Moreover, dependence of surface run-off on precipitation, which is seasonally variable, is projected to increase. These spatially and temporally non-uniform changes in water supply, together with basin-specific increases in water demand, are expected to lead to diversified changes in water stress conditions: increased water scarcity in the Indus and Amu Darya River basins and decreased scarcity in the Yangtze and Yellow River basins.

However, current understanding of the AWT and its dynamic responses to climate change are still inadequate, which limits our capacity to reliably predict its future in a warmer world and assess mitigation and adaptation strategies. We identify and propose several priorities for future research to redress these deficiencies.

First, an accurate understanding of the AWT is highly dependent on reliable monitoring and collection of climatic, cryospheric and hydrological data. However, current meteorological stations on the AWT are mostly located below 5,000 m, and less than 0.1% of the AWT's glaciers and lakes have monitoring stations[63]. The necessary expansion of monitoring networks should consist not only of automatic weather stations but also measurements of stable isotopes in water along a south–north (monsoon-dominated) transect stretching from the tropical Indian Ocean across Nepal to the Tien Shan, and an east–west (westerlies-dominated) transect from the Iranian Plateau to the Loess Plateau in China[63]. These two transects could provide critical information on changes in atmospheric moisture linked to the dynamics of the Indian monsoon and mid-latitude westerlies, physical processes that affect precipitation, glacier melt and lake volume, and the interconversion of water between solid, liquid and vapour phases. Moreover, plateau-scale measurements of snow (in water equivalent), groundwater and evapotranspiration are the most challenging but most important components of studying water balance over the AWT. Another major challenge, which has not yet been sufficiently addressed, is to

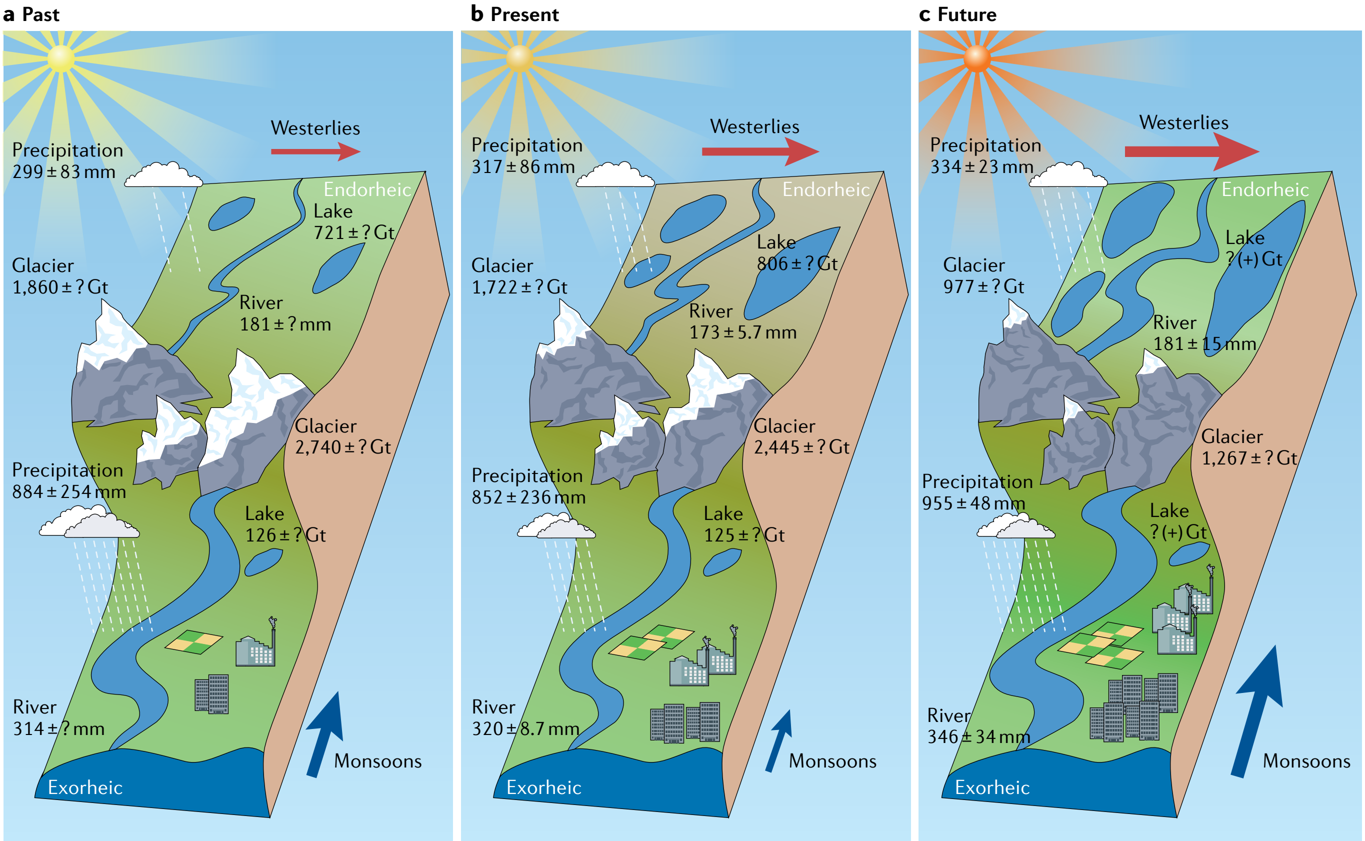


Fig. 5 | **Schematic of the status of the Asian water tower in the past, present and future. a–c** | Past (1980–1990) (part **a**), present (2006–2015) (part **b**) and future (2080–2100) (part **c**) of the Asian water tower (AWT). Red arrows indicate strength of mid-latitudinal westerlies and blue arrows strength of Indian summer monsoon. Predicted changes in precipitation, run-off and glacier based on World Climate Research Programme (WCRP) Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations under a moderate warming scenario (representative concentration pathway (RCP) 4.5). Uncertainties of precipitation in past and present periods estimated from various precipitation products: Climate Research Unit (CRU), Global Precipitation Climatology Centre (GPCC), Global Precipitation Climatology Project (GPCP), National Centers for Environmental Prediction (NCEP), Fifth Generation European Centre for Medium-Range Weather Forecasts Reanalysis (ERA5), Japanese 55-Year Reanalysis (JRA55) and Indian Monsoon Data Assimilation and Analysis (IMDAA). Uncertainties in projected precipitation changes derived from CMIP5 spread in precipitation projections.

monitor permafrost degradation, which is a significant contributor to surface run-off. Satellite data are crucial for large-scale monitoring. For example, the GRACE and Surface Water and Ocean Topography (SWOT) missions[149] can provide broad-scale observations of groundwater storage and the area and depth of lakes. One of the major aims of the Second Tibetan Plateau Scientific Expedition and Research Program (STEP) is to obtain data on the water budget through integrating and improving in situ and satellite-based multi-spheric monitoring networks.

Second, Earth system models are useful for generating projections of future water resources, and their output could guide regional strategies for climate mitigation and adaptation. The AWT is a complex regional Earth system with strong multi-spheric interactions between the atmosphere, cryosphere, hydrosphere, biosphere and anthroposphere. However, current models cannot realistically represent aspects of precipitation changes derived from atmospheric dynamics and the resultant hydrological changes[26,150]. Moreover, the spatio-temporal resolution of current models is insufficient to simulate the hydrological dynamics of the AWT. We propose that an AWT Earth system model should be developed that could represent its multi-spheric interactions accurately and at very high resolution, encompassing stable isotopes as tracers of the water cycle, which could provide unique constraints on how water is evaporated and transported from different moisture sources[151].

Third, current data and models indicate increasing run-off originating from the AWT, which results in two critical challenges. The first challenge is the inter-seasonal and inter-annual variations in surface run-off, which are likely to increase as a result of imbalance of the AWT, which will have severe consequences for downstream areas (some more than others). However, current knowledge of such variations is limited. For example, warming generally decreases the proportion of precipitation that falls as snow versus rain[152,153], thereby reducing winter snowpack, melting of which provides an important buffering of the water supply to downstream areas during the warm season or in dry years[8]. This change would lead to an intensification of seasonal water shortages as well as a shift in the time of peak run-off and/or increased flood risk. More research is needed to understand seasonal and inter-annual redistributions of water supply from the AWT and inform climate adaptation and mitigation measures. The second challenge is permafrost thawing[62,154] and ice melting in rock glaciers[65,155–158]. Permafrost thawing deepens the thickness of the active layer, which contributes to reduced surface run-off by soaking up more infiltrating water[159–161]. At the same time, rock glacier melting could increase river run-off. The effect of these two processes on water resources in the AWT remains unquantified, highlighting an urgent necessity of including permafrost ice and associated freeze–thaw processes in Earth system models[21,162,163]. Moreover, ongoing warming-induced glacier melting and permafrost thawing in the AWT is very likely to irreversibly change the balance of this system at some point in the future, disrupting the supply of run-off to downstream areas and losing its water tower function. A pressing need exists to identify and quantify such irreversible tipping points of the future AWT and to design actions to avoid crossing them.

Fourth, the capacity of developing nations downstream of the AWT to adapt to changing water resources, as well as to respond to flooding, droughts and other environmental hazards, remains much lower than that of developed countries. A major challenge is to build a cost-effective, evidence-based adaptation plan for integrated water resource management. The complexity of the AWT imbalance indicates that such a plan could only be made possible through multidisciplinary efforts spanning the fields of climatology, glaciology, hydrology, ecology, geography, geology and social sciences. In addition to an adaptation plan, a critical challenge is the collaboration of all stakeholders, including, but not limited to, residents, scientists, policymakers and international organizations. Ultimately, transnational water cooperation requires participating countries and stakeholders to provide accurate information about the status of basin-wide water resources and hazards. A monitoring network that integrates all water resource components (glaciers, groundwater and run-off) that contribute to a given transboundary river and basin-specific hydro-economic system models should be constructed and developed collaboratively by all parties, with a special focus on filling the gaps in data-sparse regions. Such a monitoring network could promote scientific research and provide an objective account of water resource status and trends, as well as raising basin-wide awareness of the challenges posed by water scarcity, and spur transboundary water management activities. Only by solving these challenges and enhancing the capacity of downstream countries to adapt to the imbalance of the AWT will we be able to achieve a sustainable future for Asia and the world.

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Author contributions
T.Y. designed the Review. T.Y., S.P., G.Z., T.W., W.Y., J.G., L.W., F.S. and P.Z. wrote the first draft of the manuscript. T.B., D.C., L.T., W.I., W.Y., B.X. and G.W. reviewed and edited the manuscript. All authors made substantial contributions to discussions of its content.

Competing interests
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