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Flexibility and intensity of global water use

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Water stress is often evaluated by scarcity: the share of available water supply being consumed by humans. However, some consumptive uses of water are more or less flexible than others, depending on the costs or effects associated with their curtailment. Here, we estimate the share of global water consumption over the period 1980–2016 from the relatively inflexible demands of irrigating perennial crops, cooling thermal power plants, storing water in reservoirs and supplying basic water for humans and livestock. We then construct a water stress index that integrates the share of runoff being consumed (scarcity), the share of consumption in these inflexible categories (flexibility) and the historical variability of runoff weighted by storage capacity (variability), and use our index to evaluate the trends in water stress of global major river basins on six continents. We find that the 10% most stressed basins encompass ~19%, 19% and 35% of global population, thermal electricity generation and irrigated calorie production, respectively, and some of these basins also experience the largest increases in our identified stress indexes over the study period. Water consumption intensities (water used per unit of goods or service produced) vary by orders of magnitude across and within continents, with highly stressed basins in some cases characterized by high water consumption intensities. Our results thus point to targeted water mitigation opportunities (for example, relocating crops and switching cooling technologies) for highly stressed basins.

Freshwater is an essential resource for modern civilization, fundamental to food and energy production[1–4]. Globally, irrigated agriculture is the largest water consumer, accounting for ~85–90% of water consumption[1,2,5], followed by industrial (for example, water for cooling power plants) and domestic water use, along with evaporative losses from reservoirs[1,3]. Given the dependence of humans, livestock, food and energy systems on water[1–4], rising demands for food and energy[1,5,6] and recent and projected increases in the frequency and severity of droughts and heat waves[4,5,7,8], water stress is an increasingly important topic of research.

Previous studies have assessed water stress mainly by comparing total water use with local or regional water availability[1,2,9–11], in some cases projecting trends in water use and climate cha nge[2,4–6,12–14]. Although previous results may help to anticipate future water scarcity, they indicate little about the geographical and technological priorities for adaptation and reducing stress. There may be large differences in the relative flexibility of various water uses in different places and similarly large differences in the associated intensity of those uses (for example, water used per unit of good or service produced).

Here, we demonstrate a method for assessing water stress that takes into account not only water scarcity but also the flexibility of water uses and the variability of water supply. We report results as a water stress index (of scarcity–flexibility–variability, SFV) that is applicable at scales from catchments to continents. Details of our analytical approach are described in Methods. We first analyse patterns of global total water consumption from 1980 to 2016 in the agriculture, energy and domestic sectors, focusing on categories of consumption that we define as 'inflexible' where curtailment would lead to large and irreversible losses of capital investments or human lives[15–18]. For inflexible consumption, we include: (1) freshwater consumed for irrigation of perennial crops, (2) water evaporated during cooling of thermal power plants, (3) water evaporated from reservoirs and (4) basic water allotments for humans and livestock. The resulting SFV water stress index (ranging from 0 to 100) compares both total consumption and inflexible consumption to mean surface runoff (for example, overland runoff including throughflow, as defined in the modern-era retrospective analysis for research and applications, v.2, MERRA-2 reanalysis dataset[19]), as well as the historical variability in surface runoff (represented by the coefficient of variation) inversely weighted by the ratio of local storage capacity to average runoff (referred to hereafter as 'weighted variability'). A high weighted variability of historical runoff means that inter-annual fluctuations in surface water supplies are large relative to water storage in a given basin, thus posing extra challenges to water managers seeking to reliably meet demands in the basin (see Methods).

Implicit in our characterization of inflexibility are the disparate costs of curtailing water consumption. For example, fallowing annual crops results in lost revenues but not lost capital, whereas curtailing irrigation of perennials may result in the loss of years of time and thousands of US dollars per acre in establishment costs[16,18]. Thus, the curtailment costs for perennial crops can be expected to be much higher than those for annual crops as shown in Supplementary Table 1. A case study of the 2011–2016 California drought found that most land fallowed was in annual crops, while effects on more valuable perennial crops were largely avoided because of continued irrigation[16,18]. Similarly, idling power plants due to unavailability of cooling water results in substantial curtailment costs related to lost revenues (Supplementary Table 1), making it among the last use of water to be curtailed, even without considering the critical role of electricity in the broader economy[20], the comparative difficulty of trading electricity[21] and the potential for immediate and amplified damages to economic productivity and human health in the event

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of power outages[22,23]. Additionally, substantial values of livestock may be lost if animals are not watered (Supplementary Table 1) and invaluable people's lives might be lost without sufficient supplies of basic water[24]. Finally, storage reservoirs, with an average lifetime of 75 years[25], generally represent substantial capital investments, whose removal or emptying may or may not be feasible, depending on their primary purposes (for example, seasonal storage for agriculture, flood protection and hydroelectricity generation); any water savings would also be delayed by the time required for planning. Given our global scope, we provide only one way to classify inflexible water consumption. Depending on the setting and scale of analysis, 'inflexible' consumption could be defined differently.

Our estimates of grid-level (5 arcmin) crop- and year-specific irrigation water consumption are based on the Global Crop Water Model (GCWM)[26] and national statistics of irrigated areas from the Food and Agriculture Organization (FAO)[27], thereby reflecting both inter-annual weather variations and changes in crop patterns (see Methods and Supplementary Methods). We estimate water consumption by the power sector at the level of ~58,000 individual generating units, using information about the type of generator and cooling system from the World Electric Power Plants (WEPP) database[28] and local meteorological data extracted from the MERRA-2 reanalysis dataset[19] (see Methods and Supplementary Tables 2–4). Our estimates of evaporation from reservoirs also rely on the local meteorological data from MERRA-2; reservoir locations and surface areas are from the Global Reservoir and Dam database (GRanD)[29]. Concerning water availability in each year of 1980–2016, we focus on grid-level annual average sustainable water supply: historical surface runoff, which is also derived from MERRA-2. We aggregate and report results at the scale of ~400 global major river basins, as defined by the Global Runoff Data Centre (GRDC)[30].

By resolving details of infrastructure, cropping patterns and local weather conditions, our results reveal considerable spatial differences in the intensities of water consumption. Such differences suggest targeted opportunities for alleviating water stress by improving infrastructure or relocating specific activities.

Trends in global water demand

Global water consumption rose from ~1,200 km^3 in 1980 to ~1,700 km^3 in 2016 (a 40% increase; Fig. 1a). Although inflexible water consumption increased from 460 to 590 km^3 over the same period, the share of inflexible consumption decreased slightly from 38% in 1980 to 34% in 2016. This slight decrease is because total flexible water consumption increased somewhat faster (a 50% increase from 750 to 1,130 km^3). During this period, most of the increases in inflexible consumption occurred in irrigation of perennials (from 85 to 140 km^3) and reservoir management (from 320 to 360 km^3), similar to the percentage increases in agricultural area equipped for irrigation (which rose by 48% from 270 to 400 × 10^6 ha) and dam capacity (which rose by 20% from 4,700 to 5,600 km^3), respectively. Likewise, water consumption for thermal power generation almost tripled from 6.5 to 19 km^3, whereas basic water consumption for humans (33–54 km^3) and livestock (14–17 km^3) increased by 60% and 25%, respectively. Changing trends for various water consumption are mainly due to changes in human activity (for example, dam capacity, power generation and irrigated area expansion), with variability in meteorological conditions playing a smaller role.

Overall, reservoir management accounted for 21% of water consumption in 2016 (60% of total inflexible consumption) and irrigation of perennial crops accounted for another 8% (24% of total inflexible consumption; Fig. 1b). Reservoir management is also a large source of uncertainty in our estimated total and inflexible water consumption (Supplementary Fig. 1). Water consumption for humans, livestock and thermal power generation each contributes roughly 3%, 1% and 1% of total water consumption, respectively. Although the share of water consumption by thermal power is small, 69% of the reservoir management water consumption is due to dams primarily designed for hydroelectricity generation (Fig. 1c). Thus, total electricity generation could potentially constitute 15% of global total water consumption or 45% of total inflexible water consumption. Likewise, dams designed primarily for irrigation are responsible for 14% of reservoir-management water consumption, which further increases total water consumption for irrigation. Concerning thermal power, coal-fired power plants account for over half of global water consumption for thermal electricity generation, with most of the rest coming from nuclear (15%), waste heat (14%), natural gas (7%), biomass (4%) and oil (3%) power generation (Fig. 1d). Among perennial crops, citrus and date palm make up approximately 19% and 8% of total perennial irrigation water consumption, respectively, with the rest primarily consumed by an aggregate of over 50 other types of perennials[31] (Fig. 1e). Cattle alone represent 80% of total livestock water consumption (Fig. 1f).

Constructing the SFV water stress index

We assess and integrate three factors in our SFV water stress index for global major river basins (Fig. 2), beginning with physical water scarcity relative to consumptive demands. Basins where more than 55% of local mean runoff is consumed (the top 10% basins in Fig. 2a, shown in dark red) are concentrated in Asia, western North America and small basins in Western Europe and South America. Such basins have been identified by previous studies as having high water scarcity[2], where meeting demands typically requires additional water supplies from groundwater, storage or cross-basin transfers.

Second, we evaluate the share of runoff consumed by inflexible demands. Because these inflexible demands represent a subset of total demand in a given basin, the ratio of inflexible consumption to mean runoff (Fig. 2b) is always smaller and usually much smaller than the ratio of total consumption to runoff. Yet the ratio of inflexible water consumption to runoff follows a different spatial pattern than the physical water scarcity, particularly in regions with relatively large population (Supplementary Fig. 2a). Only some of the basins that stand out in Fig. 2a are dominated by perennial agriculture, reservoirs, drinking and power sector water consumption.

Finally, the weighted variability of annual mean runoff tends to be consistently low at high northern latitudes (blue- and green-shaded basins in Fig. 2c). However, this value is much higher in Africa, Australia and some small basins in South America (orange- and red-shaded basins in Fig. 2c), indicating that inter-annual variations in historical runoff are large relative to reservoir storage in these basins.

The SFV water stress index reflects the combination and equal weighting of the three components of share of runoff consumed, the (in)flexibility of water demands and weighted variability of runoff. Figure 3 shows this SFV index for each major river basin. We find that, globally, the 10% most stressed basins are concentrated in Central and East Asia, western North America, Australia and northeastern Africa; these areas encompass regions with roughly 19% of global population, 19% of the world's thermal electricity generation and 35% of global irrigated calorie production. In turn, these basins account for 15% and 31% of global inflexible and total water consumption, respectively.

Compared to the spatial distribution of physical scarcity (Fig. 2a), our SFV water stress index (Fig. 3) reveals important differences. For example, the basins that show up as most stressed in Fig. 3 do not always consume large shares of runoff in Fig. 2a. Indeed, some of the 20% most stressed basins in our study (for example, the Cunene, Ntem and Messalo basins in Africa and the Leichhardt and Flinders river basins in Australia) consume less than 2% of local runoff but over 50–100% of all water demands in these basins are inflexible and historical variations in runoff are substantial compared to available storage (for example,

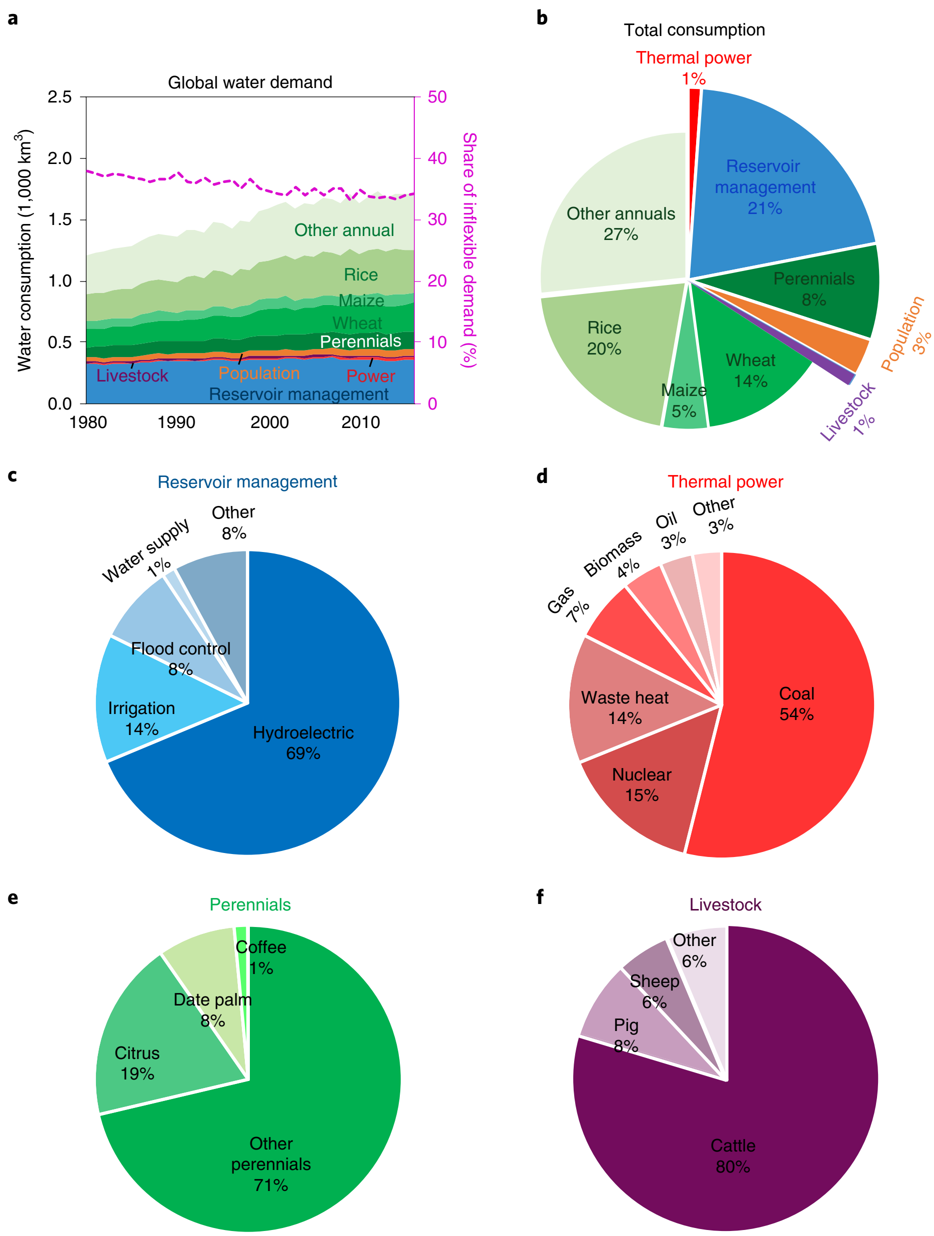

Fig. 1 | Global and sectoral water consumption. a, Historical inflexible water consumption from reservoir management (blue), thermal power generation (red), livestock (purple), human population (orange) and perennial crops irrigation (dark green), as well as flexible irrigation water consumption from annual crops (wheat, maize, rice and other annual crops; light green). **b**, 2016 percentage contributions of flexible (smaller pie) and inflexible (bigger pie) water consumption to global total water consumption. **c**–**f**, 2016 inflexible water consumption from reservoir management by main dam purposes (**c**), thermal power generation by fuel types (**d**), irrigated perennials by crop types (**e**) and livestock by species (**f**).

the weighted coefficients of variation are ~0.9–1.2). Conversely, basins such as the Mississippi River, Ulua and Yaqui in North America, Incomati (Africa), Ural (Asia) and Don (Europe) are among the top 20% basins with respect to the share of runoff consumed, but according to our new index are not particularly stressed—indexes are all ≤6 (the median SFV score, Fig. 3) due to low shares of inflexible demand and small weighted variations in local water supply. We illustrate such differences in greater detail in Supplementary Fig. 2b. Several basins in Central Africa and Australia (yellow- and red-shaded) are emphasized as stressed by the SFV index in contrast to only focusing on physical water scarcity (Fig. 2a), while many basins in North America, South America, Europe and South Asia (blue- and green-shaded) are de-emphasized compared to Fig. 2a.

Regional hotspots with high stress and exposure

Across basins, substantial variations exist not only in water stress but also in the exposure of human activities to water stress. We define exposure as the total human population, livestock head, reservoir capacity, electricity generation and caloric production of irrigated crops (see Supplementary Methods). Regions with both high stress and large exposure are primarily concentrated in Asia and North America (Figs. 3–5).

To capture region-specific characteristics, we select one basin from each continent (Supplementary Fig. 3). In each of the six major continents, we select the basin that has the highest SFV water stress index among those with the top 10% exposure (Figs. 3 and 4; Supplementary Methods). We then evaluate the relative contributions of each factor shown in Fig. 2 to each selected basin's SFV

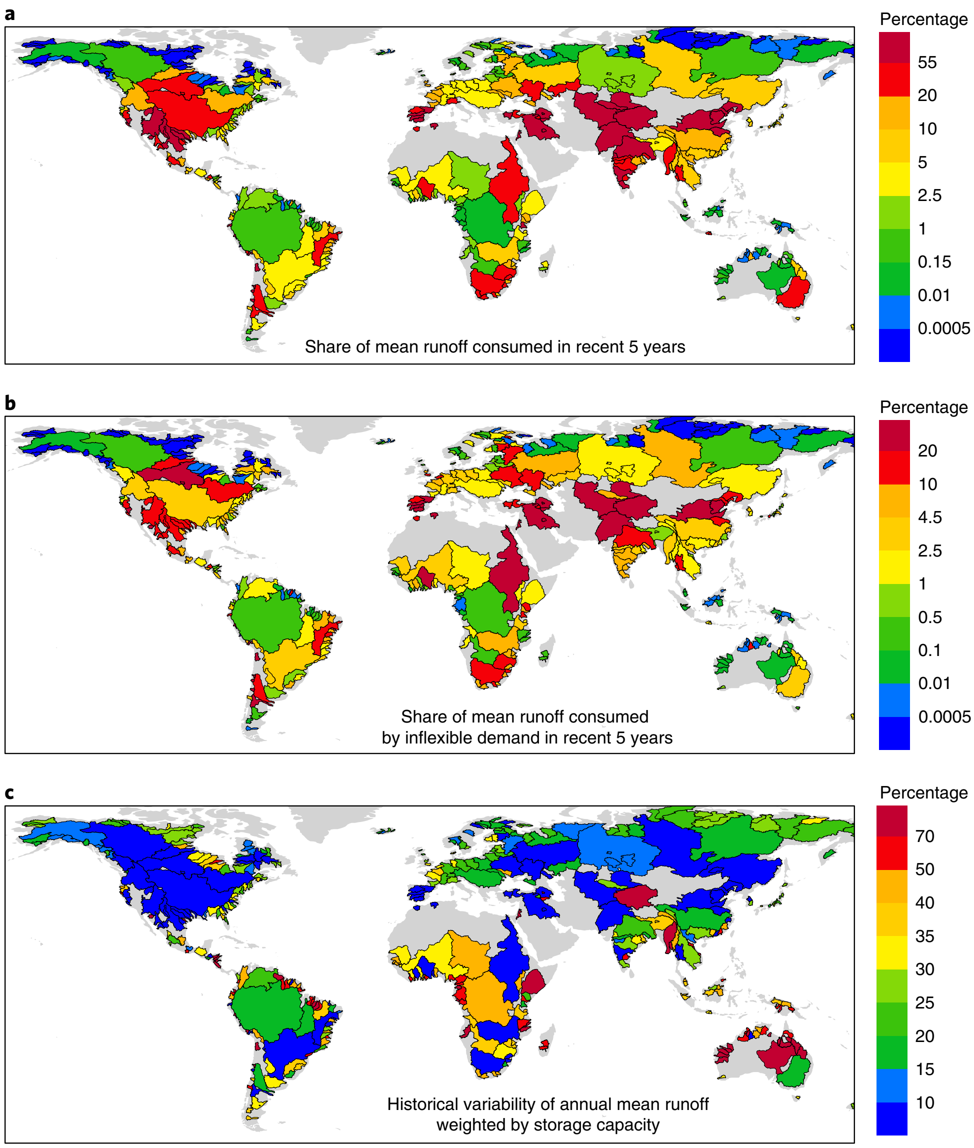

Fig. 2 | Global maps of three factors contributing to the SFV water stress index. a, Ratio of recent 5-year average (2012–2016) total water consumption to historical annual average runoff. **b**, Ratio of recent 5-year average (2012–2016) inflexible water consumption to historical annual average runoff. **c**, Reservoir storage weighted coefficient of variation of historical runoff for global major river basins from the river mouths at the erosion base level as defined by the GRDC[30]. Grey areas are not mapped as hydrological basins in GRDC due to no ocean outlet. Colour bars in each panel are approximately their corresponding 10th to 90th percentiles. Default coastlines are from NCL/NCAR: http://www.ncl.ucar.edu/citation.shtml (ref. [59]).

index. The share of mean runoff consumed by inflexible demand strongly influences our stress index in each continent's selected basin with the exception of Australia, where SFV is mainly affected by the weighted variability in historical runoff.

The relative contribution of different water uses to total water consumption varies substantially across our selected basins (Fig. 4). Water consumption in Tigris/Euphrates, Tejo and San Joaquin are dominated by relatively flexible annual crop irrigation, followed by inflexible perennial crop irrigation and reservoir management. Water consumption in Fitzroy and Magdalena are dominated by annual crop irrigation, followed by reservoir management. In comparison, water consumption in Nile is dominated by reservoir management.

The absolute values of total water consumption and runoff across basins also vary by orders of magnitude, ranging from ~1 to 200 and ~1 to 600 km^3, respectively (Fig. 4). This range causes substantial variations in the comparisons between water consumption and runoff. Annual total runoff in Tigris/Euphrates is lower than both total and inflexible water consumption for most of the years, while only occasionally below total and/or inflexible water consumption in Nile and Tejo. In contrast, runoff in San Joaquin is mostly below total but above inflexible water consumption, while the yearly runoff in Fitzroy and Magdalena have been consistently greater than the total and inflexible water consumption. As a result, the share of mean runoff consumed by inflexible demand varies greatly across basins (1–350%) and also across years (by an order of magnitude; Fig. 4).

Recent average water stress indexes for the six selected regional basins range from ~7 in South America to ~55 in Asia (Fig. 4). This finding indicates that Asia (and North America, to a lesser degree) may face the most risk due to the co-location of regions with high stress indexes and regions with large exposure (Figs. 3–5). High stress in these regions will put substantial human population, livestock, electricity generation, food production and reservoir capacity

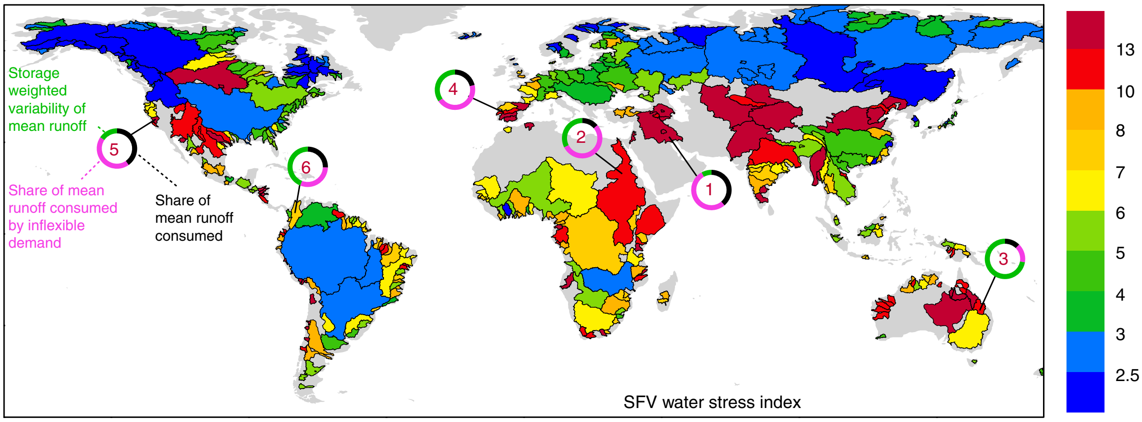

Fig. 3 | Recent 5-year (2012–2016) average water stress indexes (SFV) for global major river basins in this study. The selected basins in each continent (Asia, Africa, Australia, Europe, North America and South America) are labelled 1–6, respectively. In each continent, the basin is selected as the one having the largest water stress index among the top 10% basins that have substantial electricity generation, crops production, human population, livestock and dam capacity in each continent. The six doughnut diagrams represent the percentage contributions of the three factors shown in Fig. 2 to the overall stress index in each of our selected basins. Colour bars are approximately the corresponding 10th to 90th percentiles. Global major river basins are defined in GRDC[30]. Default coastlines are from NCL/NCAR: http://www.ncl.ucar.edu/citation.shtml (ref. [59]).

at risk. In contrast, in other continents, basins with high exposure generally have much lower stress indexes. Although there are basins with higher stress indexes than the selected basin in these continents, exposure (population and production activities) in those more-stressed basins are much lower than in the selected basin.

Over the study period, variations in water stress indexes for our selected basins are generally small (<20%), except for Tigris/Euphrates (>90%), which shows a notable increasing trend (slope of 0.8 yr^{-1}) (Fig. 4 and Supplementary Fig. 4), mainly due to substantial increases in irrigation water consumption (>20 km^3) and slight decreases in annual historical runoff. In comparison, increases in total water consumption in other selected basins are usually much smaller (<1 km^3). Total water consumption increase is also high in the Nile basin (~15 km^3); however, this increase is largely offset by notable increases in runoff. Therefore, stress indexes in basins other than Tigris/Euphrates mostly only show a slightly increasing (or even decreasing) trend over the years (slope <0.05 yr^{-1}; Supplementary Fig. 4b). Notably, some of the most stressed basins, particularly those in Asia, also experience the largest annual mean increases in stress indexes (Supplementary Fig. 4).

Opportunities to reduce inflexible water consumption

Although curtailing inflexible water consumption is associated with higher costs and socio-environmental consequences, opportunities exist to reduce inflexible water consumption, which, however, usually takes a relatively long implementation period. Here we evaluate the basin-level average water consumption intensities for per unit electricity generation, calorie production and dam capacity in each continent, respectively (Fig. 5). Different continents have varying levels of water stress and water consumption intensities. Across continents, the median water consumption intensities for thermal power generation are comparable, ranging from 1.1 (South America) to 1.4 (Australia) $m^3\,MWh^{-1}$. However, there are much larger variations in the median water consumption coefficients for perennial production and reservoir management. In particular, the median water consumption intensities for perennial production vary from 0.0003 (0.3 l $kcal^{-1}$) (Europe) to 0.01 (10 l $kcal^{-1}$) (Australia) $m^3\,kcal^{-1}$. Additionally, the median water consumption intensities for reservoir management vary from 0.03 (Asia) to 0.12 (Australia) m^3 consumed per m^3 capacity, respectively. Continental variations in water consumption intensities are particularly high for perennial crops irrigation, reflecting large spatial heterogeneity in crop types, irrigation practices and regional climate.

Within each continent, we observe variations of roughly 2–3 orders of magnitude in average water consumption intensities of thermal power generation (ranging from 0.1–4.9 $m^3\,MWh^{-1}$ in Asia to 0.01–6.2 $m^3\,MWh^{-1}$ in Europe), 2–6 orders of magnitude for perennial production (ranging from 0.001–0.05 $m^3\,kcal^{-1}$ in Australia to 2e-8–2e-2 $m^3\,kcal^{-1}$ in North America) and 1–2 orders of magnitude for reservoir management (ranging from 0.03–0.16 m^3 consumed per m^3 capacity in Australia to 0.005–0.28 m^3 consumed per m^3 capacity in North America). Unexpectedly, we notice that basins with high stress indexes can have both high and low water consumption intensities (Fig. 5). Thus, there seems to be no consistent relationship between a basin's stress index and its water consumption intensity even within a given continent.

The decoupling of water stress and water consumption intensity indicates that current water management fails, at least in places, to consider existing water stress when planning water use. Meanwhile, orders of magnitude variations in average water consumption intensities suggest opportunities to improve water consumption efficiencies, especially for the most stressed basins. Although water consumption intensities are affected by local climate, which is beyond our intervention, technologies and/or management practices are available to improve water consumption efficiency[11,32–41]. Supposing all of the above-average-intensity basins were to reduce water consumption intensities to the continental median value, water consumption could be reduced by 14%, 49% and 42%, for thermal power generation, perennial crops irrigation and reservoir management, respectively. Across the six continents, the largest potential reductions for thermal power generation (1.0 km^3) and perennial irrigation (21.1 km^3) are in Asia, and in Africa (63 km^3) for reservoir management.

To illustrate potential opportunities for inflexible water reduction at the basin level, we select the Balkhash (Asia), Tigris/Euphrates (Asia) and Nile (Africa) basins, which have both high water stress indexes and high water consumption intensities for generating per MWh electricity, producing per kcal irrigated perennial crops and maintaining per m^3 dam capacity, respectively (Fig. 5). Concerning water consumption for thermal power generation in the Balkhash basin, we find that switching to dry cooling technologies could reduce its total thermal power water consumption by 95%. Similarly, in the Balkhash basin, switching to low (for example, natural gas) or no (for example, wind) water-consuming cooling technologies or switching to non-fresh (for example, saline or brackish) water resources, could reduce thermal power water consumption by 44% (or 100% if switched to wind power) and 90%, respectively. To control perennial water consumption in the Tigris/Euphrates basin, one strategy is to limit the expansion of perennial crops. Also, as summarized in Siebert and Doll[26], water consumption coefficients vary greatly across crop types, indicating a potential strategy to improve water consumption efficiency through crop substitutions[32]. Another approach is to increase crop water productivity (crop yields per drop) either by increasing total yields or reducing non-productive water consumption (for example, through using conservation tillage and mulching with organic residues or by adopting more efficient sprinkler or drip irrigation systems)[33–35]. Additionally, to reduce water evaporation from dams in the Nile basin, potential effective measures include photovoltaic floating covers, monomolecular films, suspended shading covers, which could reduce evaporation by roughly 30%, 10–40% and 50–90%, respectively[36–41].

Discussion and conclusions

Building on previous efforts to assess geographies of water stress based on the share of water consumed[1,2,9], our results highlight the implications of different water consumption around the world. In particular, we suggest that some water demands are less flexible than others and that perennial agriculture, electricity generation, water storage and drinking are among such inflexible uses. In turn, inflexible demands may limit adaptive responses in the face of water shortage and thus increased vulnerability. However, because intensities of water consumption (water used per unit of good or service produced) vary by orders of magnitude across water-stressed basins, our analysis also points to strategic opportunities for increasing basins' resilience to future water shortages.

Where stressed basins host substantial agricultural production, electricity generation or reservoir storage, evaluation of water consumption intensities of agricultural crops, electricity generating and dam infrastructure may help policymakers and water managers to identify opportunities to both save water and build resilience. Savings might be realized by technological interventions or by selectively replacing domestic production with imports. This is particularly true for inflexible consumption like perennial crops, power and reservoir infrastructure, where decisions often represent decades-long commitments to produce (and use) water which would be very costly to reverse and may lead to unintended feedbacks (for example, worsening water shortages due to reservoirs)[42]. Of course, any decision affecting the energy and food sectors should also evaluate the global food–energy–water–climate interactions to ensure that effects are not shifted elsewhere and that the system is optimized to achieve the goal of sustainable development. For instance, switching to dry cooling technologies for power generation can greatly reduce water consumption but will result in extra energy consumption, increased carbon emissions and higher costs[43,44].

Several limitations and caveats apply to our study. First, we use historical runoff to measure sustainable water supply. As groundwater can be used as an additional water source[45,46], we compare our SFV water stress map with global groundwater resources (Supplementary Fig. 5a)[47]. We find that basins with high stress indexes usually co-locate with regions with relatively low groundwater recharge rates (Supplementary Fig. 5b). Thus, groundwater resources are unlikely to de-emphasize our identified stressed basins. It is also worth acknowledging that, although our study includes the majority of global water consumption, some categories are ignored (for example, manufacturing water consumption) due to data unavailability and/or the small quantities of water consumed. Our study also does not consider the effects of local moisture recycling[48] or cross-basin water transfer[49], which can play an important role in water management in some basins.

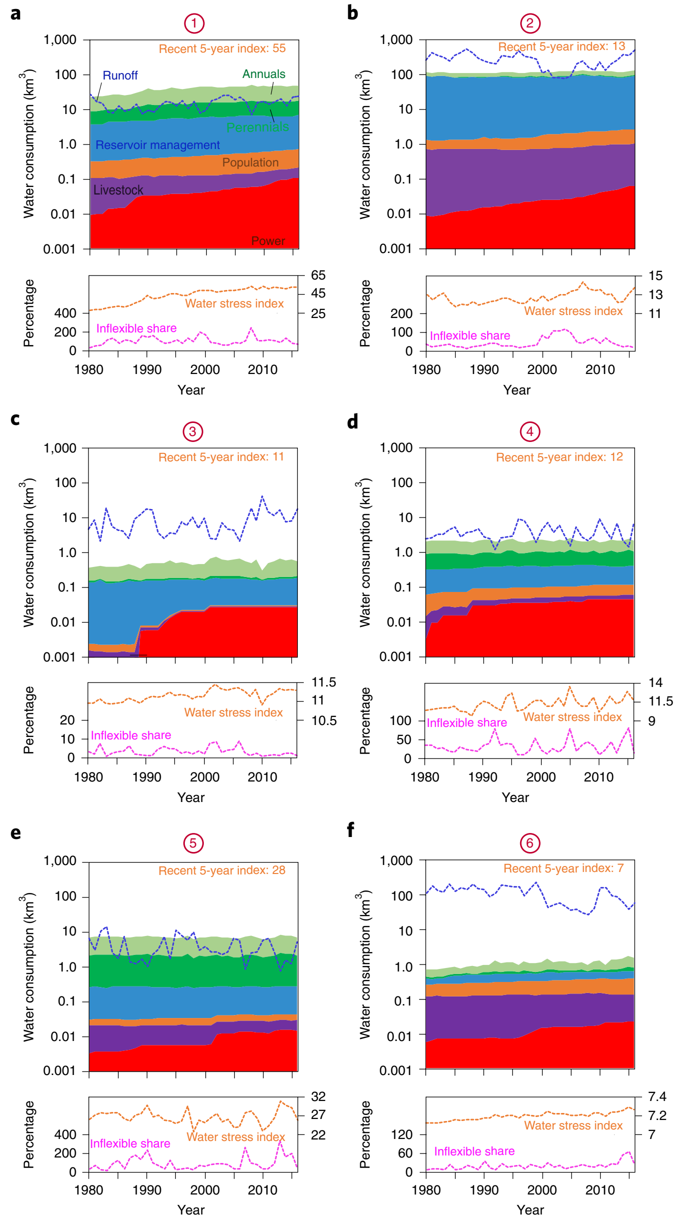

Fig. 4 | Water consumption in comparison to water availability for selected river basins in each continent as shown in Fig. 3. Inflexible share refers to the share of mean runoff consumed by inflexible demand. Recent 5-year indexes are rounded values for basin-level average water stress indexes (SFV). **a**, Tigris/Euphrates, Iraq (Asia). **b**, Nile, Sudan (Africa). **c**, Fitzroy, Australia (Australia). **d**, Tejo, Portugal (Europe). **e**, San Joaquin River, US (North America). **f**, Magdalena, Colombia (South America).

Our SFV water stress index weights scarcity, flexibility and variability equally; different weighting will therefore affect the relative scores of basins. In recognition that decision-makers in different basins may assign priority to different factors, the Supplementary Materials includes a spreadsheet of basin-specific results in which the factor weights can be adjusted. Also, as we mentioned above, 'inflexible' water consumption could be defined differently in region-specific analyses. For example, future work may improve on our work by developing region- or basin-specific curves of curtailment costs that could be used to quantitatively differentiate more and less flexible uses and the implicated water stress.

As climate change alters the regional availability of water and the characteristics of extreme drought, and human uses of

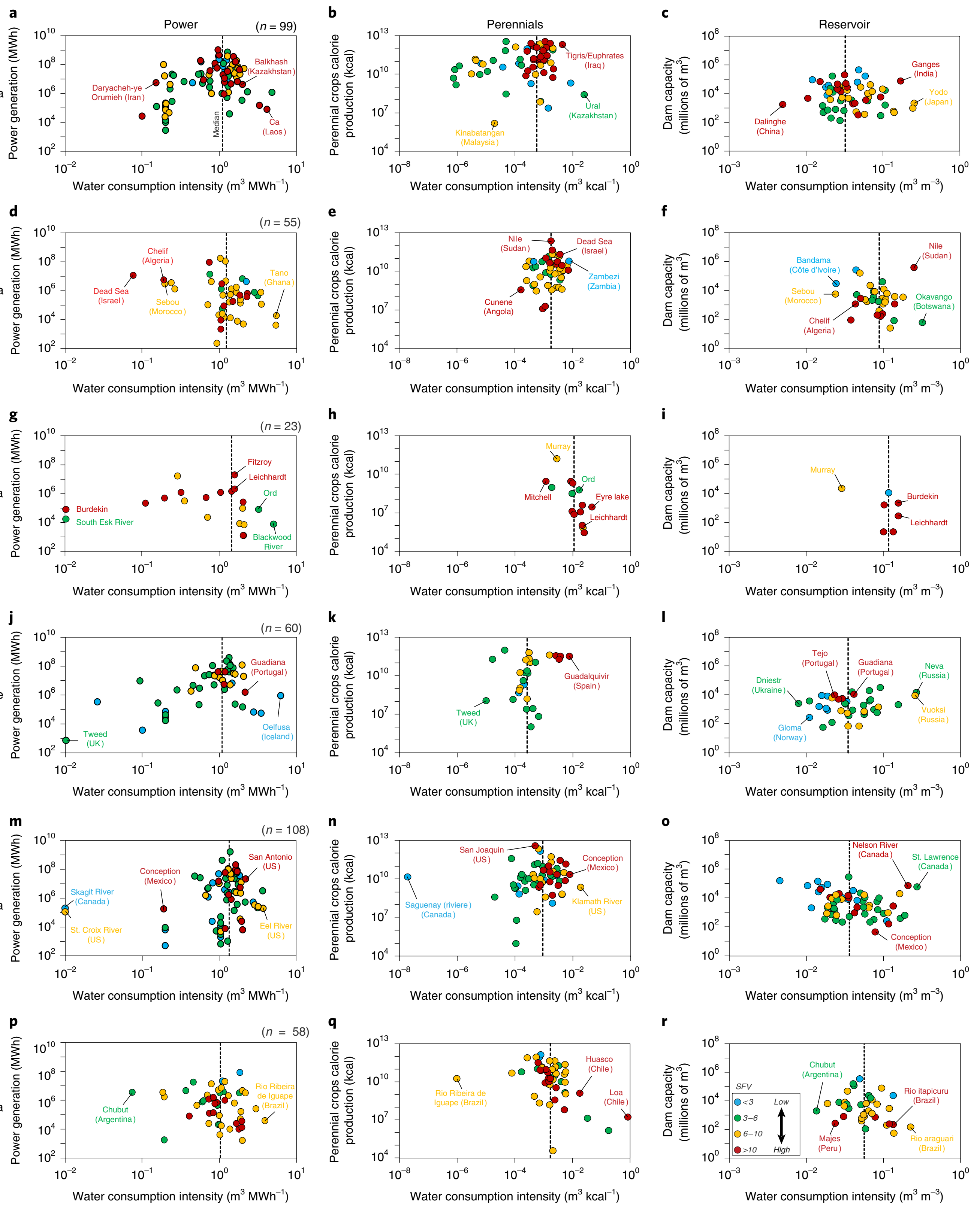

Fig. 5 | Average water consumption intensities for thermal power cooling, perennial crops irrigation and reservoir evaporation at the basin level for major continents in 2016. Panels **a**–**r** represent region- and sector-specific cases. Basin colours represent recent 5-year average water stress indexes (SFV) in each basin as shown in panel **r**. *n*, number of total basins in each continent. In each panel plot, we only show the basins that have the corresponding activity (for example, thermal power generation, perennial crops and reservoir storage).

water also increase, more detailed assessments of water use will become ever more important. Water shortages in some regions and years are inevitable; results like ours can inform planning to consume water resources as efficiently as possible while also avoiding the largest economic and health effects of such shortages.

Methods

Our study quantifies global water consumption for irrigated agriculture, energy and domestic sectors, with a particular focus on the inflexible consumption for perennial crops irrigation, thermal power generation, reservoir management and basic water requirement for humans and livestock, for the period 1980–2016.

We estimate irrigation water consumption for both annual and perennial crops on the basis of the GCWM[26] and the FAO database. GCWM characterizes green and blue water use across 26 crop classes that are inclusive of all crop types and irrigated pasture at a spatial resolution of 5 arcmin on the basis of the Penman–Monteith function as recommended by FAO[26]. Our study focuses on 'blue water' (applied irrigation water used consumptively for evapotranspiration) for irrigated crops for the period 1980–2016. GCWM has recently been run starting in 1985–2016 with yearly varying climate forcing, although the spatial extent of croplands was held fixed to the MIRCA2000 dataset (monthly irrigated and rainfed crop areas around the year 2000)[31]. To incorporate the influence of changing irrigated crop extent on irrigation water demands, we further adjust the GCWM simulated blue-water consumption by time-varying area equipped for irrigation in each country from the FAO for 1980–2015 (ref. [27]; Supplementary Methods).

We calculate unit-level inflexible water consumption for power generation on the basis of the WEPP database (2017 version)[28] (Supplementary Fig. 6). The WEPP database provides information on fuel consumption, cooling technology and installed capacity for global thermal power plants. Although WEPP includes administrative-level company information, it does not provide the corresponding geolocation. Thus, we build the geo-coordinates for each power unit by either coupling WEPP with databases that include geolocation information[50–52] or using the Google Application Programming Interface to infer geolocation on the basis of available administrative information (for example, company, street, county, city, state and/or country information). Then we extract the plant-specific yearly meteorology data from the MERRA-2 reanalysis dataset[19]. With this information, we construct the dynamic unit-level water consumption coefficients using the same equations as that of Delgado and Herzog[53] and Fricko et al.[54]. Coupling water consumption coefficients with unit-level electricity generation, we then estimate the total water consumption for individual power plant around the globe (Supplementary Methods).

Water consumption resulting from reservoir management are estimated on the basis of the GRanD database (2011 version)[29]. The GRanD database provides the reservoir capacity, geolocation, construction year, surface area of reservoir and other related information for ~6,800 global dams, which are designed for different main purposes and serve important functions to sustain human society demands (for example, hydroelectricity generation, irrigation, flood control). On the basis of the latitude and longitude information of each dam, we obtain its corresponding local meteorological conditions through coupling the GRanD database[29] with the MERRA-2 reanalysis dataset[19] and then estimate the annual total water evaporation (Supplementary Methods).

Basic water demand for humans and livestock are also calculated in this study by multiplying basic water demand per capita with the corresponding grid-level human and livestock population. Following the World Health Organization guidelines, we assume the minimum drinking and sanitation water requirement for humans are 20 l water per capita per day[55], while 25, 4, 2.25 and 0.028 l water per day for cattle, pigs, sheep/goats and chicken, respectively[56]. Due to data availability, we apply the same minimum water requirement for the same species across regions and years. Time series of global population data are obtained from the history database of the global environment (HYDE) at 5 arcmin resolution[57]. Livestock population for each species are obtained from the Geo-Wiki database (gridded livestock of the world v.2.0)[58] (Supplementary Methods).

In addition to calculating inflexible and total water consumption (water demand) for the past 37 years, we also obtain grid-level (0.5° × 0.625°) annual total historical runoff (the sustainable water supply, refers to overland runoff including throughflow[19]) for each year in 1980–2016 from the MERRA-2 reanalysis dataset[19]. We construct a new water stress index based on three factors for each of global major river basins: (1) share of historical mean runoff consumed in each year (**A**, equation (1)); (2) share of mean runoff consumed by inflexible demand in each year (**B**, equation (2)); and (3) storage capacity inversely weighted variability in annual average historical runoff from 1980 to 2016 (**C**, equations (3)–(5)). Factor **A**, representing physical scarcity, is similar to the water scarcity index used in earlier studies[2]; it captures the water stress posed by total water consumption in comparison to average water supply. Factor **B**, representing the flexibility of water use, captures the water stress posed by the inflexibility in existing infrastructure in comparison to the average water supply. Factor **C**, representing the variability of water supply, captures the water stress posed by inter-annual fluctuations in historical runoff from 1980 to 2016 (**C1**, equation (3), defined as the standard deviation over the mean of runoff), inversely weighted by the ratio of local storage capacity to average runoff (**C2**, equations (4),(5)). Greater **C** values indicate larger inter-annual fluctuations in surface water supplies relative to local water storage, thus lead to challenges for managing regional water supplies. To integrate the three factors, we normalize each of them individually using equation (6) with sample values for the entire period ($\mathbf{A}_{\text{normalize}}$, $\mathbf{B}_{\text{normalize}}$, $\mathbf{C}_{\text{normalize}}$). Global mean and standard deviation for **A**, **B** and **C** are presented in Supplementary Table 5. We then calculate the average value of the three normalized values assuming equal weights for each factor (**V**, equation (7)). All values are then linearly scaled to a stress index ranging from 0 to 100 (**SFV**, equation (8)). In this study, we use the mean of the previous 5 years (2012–2016) to represent the recent average water stress. Notably, future studies calculating this water stress index at a regional scale should normalize the parameters based on the corresponding mean and standard deviation values (**A**, **B** and **C**) in each sub-region within the interested region and time.

$$\mathbf{A}_{\text{basin } i,\text{year } j} = \frac{\text{Total water consumption}_{\text{basin } i,\text{year } j}}{\text{1980 to 2016 average runoff}_{\text{basin } i}} \quad (1)$$

$$\mathbf{B}_{\text{basin } i,\text{year } j} = \frac{\text{Inflexible water consumption}_{\text{basin } i,\text{year } j}}{\text{1980 to 2016 average runoff}_{\text{basin } i}} \quad (2)$$

$$\mathbf{C1}_{\text{basin } i} = \frac{\text{1980 to 2016 runoff standard deviation}_{\text{basin } i}}{\text{1980 to 2016 average runoff}_{\text{basin } i}} \quad (3)$$

$$\mathbf{C2}_{\text{basin } i} = \begin{cases} \dfrac{\text{Reservoir capacity}_{\text{basin } i}}{\text{1980 to 2016 average runoff}_{\text{basin } i}} & \text{if Reservoir capacity} < \text{Average runoff} \\ 1 & \text{if Reservoir capacity} \geq \text{Average runoff} \end{cases} \quad (4)$$

$$\mathbf{C}_{\text{basin } i} = \mathbf{C1}_{\text{basin } i} \times (1 - \mathbf{C2}_{\text{basin } i}) \quad (5)$$

$$\mathbf{X}_{\text{normalize}} = \frac{(\mathbf{X} - \mathbf{X}_{\text{mean}})}{\mathbf{X}_{\text{standard deviation}}} \quad \mathbf{X} = \mathbf{A}(\mathbf{A}_{i,\ldots,n}), \mathbf{B}(\mathbf{B}_{i,\ldots,n}), \text{or } \mathbf{C}(\mathbf{C}_{i,\ldots,n}) \quad (6)$$

$$\mathbf{V} = \frac{(\mathbf{A}_{\text{normalize}} + \mathbf{B}_{\text{normalize}} + \mathbf{C}_{\text{normalize}})}{3} \quad (7)$$

$$a = \frac{100}{\mathbf{V}_{\max} - \mathbf{V}_{\min}};\ b = \frac{100}{\mathbf{V}_{\min} - \mathbf{V}_{\max}} \times \mathbf{V}_{\min};\ \mathbf{SFV} = a \times \mathbf{V} + b \quad (8)$$

Data availability

Data used to perform this work can be found in the Supplementary Information. Any further data that support the findings of this study are available from the corresponding authors upon reasonable request.

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Author contributions

S.J.D., N.D.M., R.B.J., J.B.Z. and Y.Q. designed the study. Y.Q. performed the analyses, with additional support from S.S., A.A. and D.T. on datasets and S.S., C.H. and D.T. on analytical approaches. Y.Q., S.J.D., N.D.M., R.B.J. and J.B.Z. led the writing with input from all co-authors.

Competing interests

The authors declare no competing interests.

Additional information

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