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Quantifying water overconsumption using a new water supply sustainability indicator

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Abstract

Communities around the globe are experiencing great difficulty in constraining their water consumption within the limits of available, renewable freshwater supplies. When water consumed from freshwater supplies exceeds natural replenishment from snowmelt, rainfall, or aquifer recharge, freshwater sources can become depleted to the point that water shortages emerge with serious consequences for economies, human and ecosystem health, and social disruption. We describe a quantitative approach—called the “Indicator of Water Supply Sustainability” or IWSS – for assessing trends in the freshwater sources being utilized for water supply in cities, industries, power plants, and on farms, and demonstrate its use in six river basins in the western United States. Our integrated assessment approach considers trends in all affected freshwater sources including rivers, lakes, reservoirs, and aquifers, which can serve as a means for assessing water-supply sustainability and as a warning signal that water security may be jeopardized if declining trends exist and persist. Importantly, trends in freshwater sources are based on measured conditions using water data that can be accessed and evaluated for many regions around the world.

1 Introduction

The concept of sustainability gained global recognition in 1987 when the United Nations’ Brundtland Commission published its report on *Our Common Future*, [1] in which sustainable development was defined as “meeting the needs of the present without compromising the ability of future generations to meet their own needs.” In translating these sustainability concepts for application to water resources, Gleick [2] suggested that sustainable water management implies “the use of water that supports the ability of human society to endure and flourish into the indefinite future without undermining the integrity of the hydrological cycle or the ecological systems that depend on it.” In practice, application of the sustainability concept has generally been interpreted as an intent to avoid the depletion of natural resources [3].

It is important to note Gleick’s reference to the hydrological cycle. It implicitly recognizes that water-user communities such as a city or an irrigation district are in many cases extracting water from multiple sources such as a river, a lake, a reservoir, or a groundwater aquifer all within the same hydrologic basin or geographic region, and



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these water sources are commonly interconnected as part of a local hydrological cycle. For instance, reservoirs are replenished by river flows, and a river may be recharging an underlying groundwater aquifer or receiving discharge from an aquifer.

Despite the ubiquitous interconnectedness of water sources within a geographic basin or region, most evaluations of water sustainability have focused on individual water sources in isolation, e.g., aquifer sustainability is commonly assessed according to whether aquifer levels are declining, without also considering whether river flows or reservoir levels in the same region are increasing or decreasing. Yet the causation of changes in any one water source may be strongly connected to changes occurring in other water sources in the same region, either because they are physically interconnected or because multiple sources are being utilized in the same water-supply system. For instance, it is quite common for river flows to be depleted by groundwater pumping [4, 5] and there are many cases in which groundwater pumping has accelerated after river flows or reservoirs have been largely exhausted [6, 7]. These hydrologic and water management exchanges and tradeoffs emphasize the need for sustainability assessments that account for conditions and trends in multiple water sources within a water-supply system including both surface waters and groundwater.

Additionally, the practical value of water sustainability assessments will be greatly enhanced when they quantify the degree to which water consumption must be adjusted to attain a sustainable water balance. For example, the Science Based Targets Network (SBTN) has developed an approach based on Hogeboom et al. [8] that quantifies the degree (%) by which water consumption in a river basin will need to be reduced to meet environmental flow targets [9]. This approach was developed in response to corporations interested in contributing to the alleviation of unsustainable river depletions in areas where the companies have business operations or supply chain connections. Similarly, the Sustainable Groundwater Management Act (SGMA) passed in California (US) in 2014 mandates the stabilization of groundwater levels and the preparation of groundwater management plans that include quantification of the degree to which current pumping levels must be lowered to arrest groundwater declines.

However, we note that the SBTN approach focuses solely on depletion of river flows, while SGMA addresses the impacts of groundwater pumping on streamflows but does not explicitly address the influence of reduced surface water availability in increasing groundwater pumping, which is a very important consideration when developing strategies for groundwater management. This interaction is very well illustrated by Fig. 1, clearly indicating that reduced availability of surface water supplies in the San Joaquin basin in California triggers increased use of groundwater [10]. This interconnection is further illustrated by the case studies discussed in this paper.

We suggest that there is great need for an integrated water sustainability assessment approach that takes stock of inter-annual or even inter-monthly directional changes in water-supply availability from all sources that can inform the efforts of water managers and planners.

1.1 Proposal for a new water supply sustainability indicator

The basic purpose of water management is to ensure an adequate, affordable, and sustainable supply of sufficiently clean water for various needs, while minimizing negative environmental impacts and maximizing beneficial uses [11]. A holistic assessment of

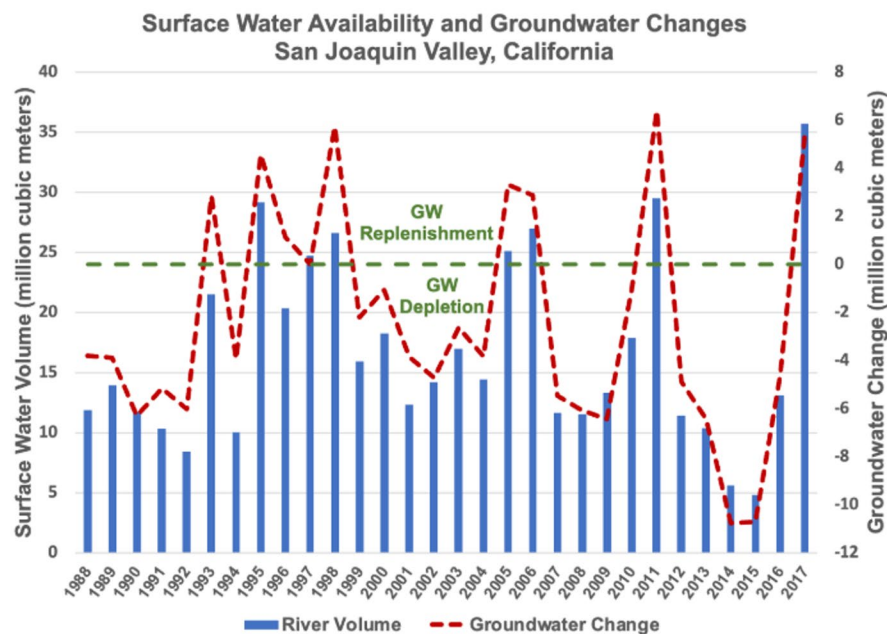


Fig. 1 Fluctuations in surface water and groundwater volumes are oftentimes tightly interconnected as illustrated here for the San Joaquin Valley in California (USA). Lessened surface water availability commonly drives increased groundwater pumping. Data source: Public Policy Institute of California

water sustainability requires examination of not just the physical hydrological system of interest but also the social and economic factors that drive changes in the physical system and an assessment of the ecological consequences of physical changes. The sustainability indicator proposed here focuses only on the status of the physical hydrological system, in the hope that its status can help water managers and other interested parties understand declining or improving trends within their entire water-supply system. These assessments can also aid corporations concerned about potential water supply risks in their business operations and supply chains.

In this paper we propose a new Indicator of Water Supply Sustainability (IWSS) for evaluating water-supply systems, which can include a single water source or multiple water-supply sources in an integrated manner. Water balances and the sustainability of human water use can be influenced by both natural and anthropogenic factors including climate variability and droughts, changing watershed conditions, and other factors in addition to anthropogenic water consumption. However, managing for long-term water sustainability requires an ability to adapt and adjust to these changing conditions over time, and balancing water consumption with the changing water supply, such that water sources are not depleted over the long term. Our indicator is therefore a measure of whether a water-supply system is being sustained in a dynamically stable condition. Mathematically, our indicator is a quotient obtained by dividing the average annual volumetric rate of change in the water sources being accessed within the system (i.e., rivers, lakes, reservoirs, aquifers) by the average annual volume of water being consumed for human purposes within a water-supply system (i.e., for municipal, commercial, industrial, power generation, mining, and agricultural uses) as follows:

$$\text{IWSS} = (\text{DReservoir volume} + \text{DGroundwater volume} \\ + \text{DLake Volume} + \text{DRiver Outflow Volume}) \\ / \text{Consumptive Water Use Volume}$$

where each variable is an average annual rate of change or volume.

A negative value of IWSS thus yields an estimate of the degree (%) to which the water-supply system is being overdrawn (i.e., unsustainable use), as indicated by a net declining volume across all of the water sources being accessed within a given water-supply system. The magnitude of a negative value indicates the degree to which consumptive uses would need to be reduced to rebalance consumption with available water supplies. In this sense, the IWSS offers a means of quantifying the magnitude of “water bankruptcy” within a water-supply system, a term that has been promoted in an effort to explain overconsumption of water supplies in a manner comprehensible to the general public [11, 12]. A positive value of IWSS indicates stable or improving conditions (i.e., sustainable use). Importantly, the numerator is based on actual measurements of volumetric change in water sources, as opposed to using hydrologic simulation models, thereby avoiding some of the inaccuracies and uncertainties in simulating the replenishment and extraction of water in complex hydrologic systems.

We note that while we do not include oceans as a water source in the numerator of our IWSS calculation, we do include the consumption of desalinated water in our denominator (total consumptive use). In this manner, the use of seawater desalination in a water-supply system will improve the IWSS value, suggesting that desalination reduces pressure on freshwater sources. Similarly, other supplementation of water supplies such as through importation of water from other water sources (i.e., inter-basin transfers) will also improve the IWSS value.

The geographical domain of IWSS assessments is flexible; it could incorporate only the specific water sources tapped by a municipal water utility or farming district, for example, or it could include all water sources utilized within a river basin or a geopolitical boundary such as a state or province. The evaluation of groundwater is based upon pumping-induced volumetric changes occurring within the portion of aquifer(s) underlying the river basin or geopolitical boundary. The river outflow component of our IWSS calculation is based on annual average volumetric changes at the outflow of the geographical domain being assessed; when a geopolitical boundary frames the IWSS analysis, there will likely be multiple river outflow points that will need to be assessed.

The time period used in calculating IWSS is flexible as well and will primarily depend upon the intent of the calculation. For instance, water managers may be interested in long-term trends (e.g., 20+ years) that span shorter-term inter-annual variability in each IWSS component, or they may be interested in assessing shorter recent periods such that response strategies can be implemented before too much hydrologic depletion has occurred. We caution that changes in groundwater and surface water levels can depend upon the proximity of groundwater pumping to surface water features such as rivers, lakes, and reservoirs. The effect of groundwater pumping on surface features can take days to years or even decades to become evident, and the rate of change in surface features caused by groundwater pumping can fluctuate over time as pumping first reduces the rate of discharge into surface features, then directly captures water from surface features, to eventually disconnecting groundwater from surface features as the groundwater

level is lowered [13]. This may suggest the need to include a sufficiently long period of record to enable detection of these complicated interactions. We also note that IWSS is based on averages for the period of record analyzed and may not be indicative of water management changes needed in the future, particularly given the influence of climate warming on water availability. Water managers may wish to investigate multiple time periods of differing lengths to answer different questions. In this paper we demonstrate the measurement of IWSS within six river basins (Fig. 2) using daily or monthly data over a common period of 22 years (2003–2024).

The ability to conduct an IWSS assessment based on measured conditions in water sources has been greatly enhanced by advances in measurement coverage, density, frequency, and accuracy over recent decades, and by improved access to these measurements in state, national, and global datasets. The specific data needed to calculate the IWSS numerator include daily, monthly, or annual measurements of the volume of water in all reservoirs, lakes, rivers, or aquifers that are being utilized as part of the water-supply system of interest. Access to these volumetric water data has improved considerably in recent years. For example, river measurements at more than 3,500 locations have been aggregated into a Global River Discharge Database [14] and many countries, states, and provinces collect and publish river flow data within their geographies. Daily volumetric measurements for more than 250 reservoirs within the US has been compiled in a ResOpsUS database [15]. Similar reservoir data can be obtained in many countries directly from the agencies managing the reservoirs.

Of particular importance is the improved ability to measure volumetric groundwater changes using the Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO) approaches [16–18]. GRACE/GRACE-FO mascon

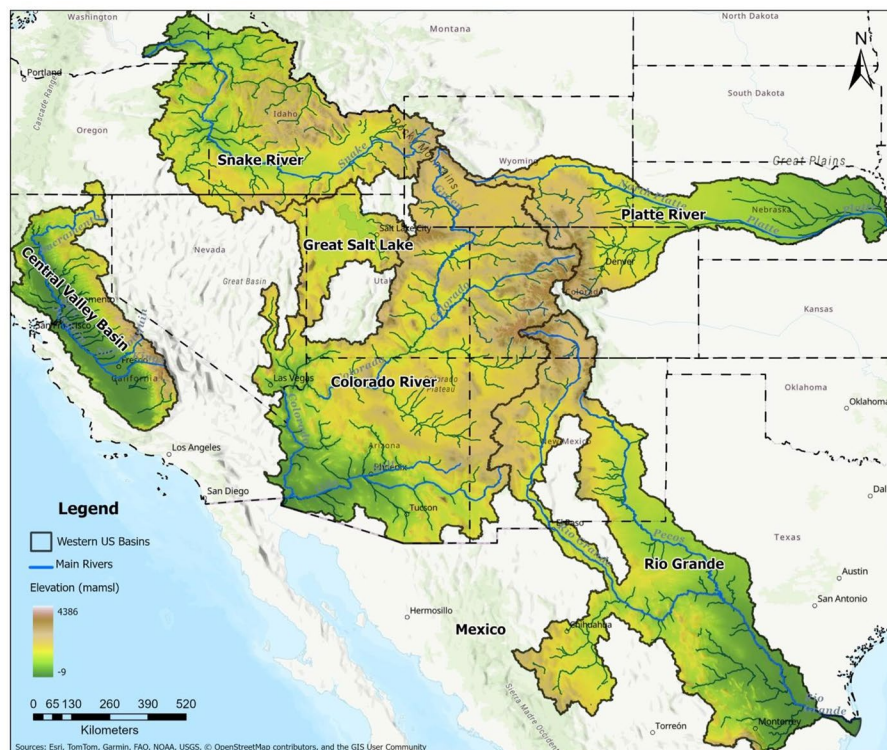


Fig. 2 Location map of six basins assessed in this study

(mass concentration) solutions are gridded gravity products derived from GRACE and GRACE-FO satellite observations that directly estimate mass changes (e.g., terrestrial water storage variations) over predefined geographic blocks, rather than relying on spherical harmonic representations [19]. This approach has led to significant improvements in GRACE data accuracy, including enhanced signal localization, reduced need for post-processing (e.g., spatial filtering), and minimized leakage errors between adjacent regions [20]. As a result, mascon solutions provide more reliable and higher-resolution estimates of basin-scale water storage changes, particularly in regions with complex hydrologic and geographic settings.

We compare changes in water source volumes (numerator) with the volumes of water directly consumed for human endeavors (denominator) in calculating IWSS; we do not include consumptive use from reservoir evaporation or evapotranspiration from riparian and wetland vegetation in our calculation because our purpose is to indicate how much reduction in anthropogenic water use is needed to attain a sustainable balance between human consumption and natural replenishment from snowmelt, rainfall, and aquifer recharge. Estimating the sum of all anthropogenic consumption is complicated by the fact that data for each water-use sector tend to be collected or estimated by different entities. For instance, water consumed for municipal and commercial (including manufacturing) purposes is typically recorded by individual municipal water agencies, and multiple municipalities may be tapping the same water source, requiring a summation across all entities using the water source. Similarly, water consumed in irrigated agriculture may be measured or estimated by an irrigation district or may need to be estimated using satellite and climate data. In the six case studies presented here, we reference recent journal papers that describe in detail the methods used in estimating each of the consumptive uses within the large complex basins assessed in this study.

2 Results: demonstrating IWSS in six western US basins

We demonstrate the calculations and findings of IWSS assessments for six basins in the western US and northern Mexico: Colorado River, Rio Grande-Bravo, Great Salt Lake, Central Valley of California, Snake River, and Platte River (Fig. 2). These basins span a wide range of climatic and hydrologic conditions as well as differing proportions of sector-specific water consumption as discussed in papers cited for each case study. The water-user communities in each of these basins rely on a combination of river, reservoir, and groundwater sources, providing illustration of varying trends and magnitudes of depletion or surplus in multiple sources. All estimates of volumetric changes are based on a common 2003–2024 time period.

2.1 Colorado River basin

The Colorado River flows southwesterly along a 2,330-km-long course from the Rocky Mountains to the Gulf of California in Mexico. It supplies drinking water to 40 million people and irrigates more than two million hectares of farmland [21]. Climate scientists have estimated that river flows have declined 19% since 2000 due to a combination of reduced precipitation and climate warming. [22]

Water managers have been unable to reduce consumptive uses to a commensurate degree, resulting in persistent overconsumption. Annual surface water consumption in this basin has exceeded natural replenishment from snowmelt and rainfall in 73% of

years since 2003 as detailed in Richter et al. [21] To make up the deficit, both reservoirs and aquifers have been depleted at a rapid rate (Fig. 3). Reservoir depletion has averaged -577.5 million cubic meters (MCM) per year, while aquifer depletion has been nearly three times greater at $-1,560$ MCM/year. We do not include river depletion in our IWSS calculations for this basin because the river has not reached its delta for much of the past half-century (i.e., Δ River Outflow Volume = 0).

Total direct human consumption, which includes a substantial volume of water exported out of the basin, has been estimated at 16,818 MCM/year [21]. A comparison of the volumetric change in reservoirs and aquifers in the basin ($-2,137.5$ MCM/yr) with human consumption yields an IWSS of -13% , indicating unsustainable overconsumption. This reveals the magnitude to which consumption will need to be reduced under an assumption that future water availability remains similar to the 22-year period assessed here. However, climate scientists have projected substantial (i.e., 20–30% by mid-century) reductions in water availability in coming decades [23], suggesting that consumptive use reductions will likely need to be much greater than 13% in the future.

2.2 Rio Grande-Bravo basin

The Rio Grande-Bravo is the fourth longest river in the US, flowing ~ 3000 km from the San Juan and Sangre de Cristo mountain ranges in Colorado to the Gulf of Mexico, forming the international border between the US and Mexico in its lower half. Along the way, the river supplies drinking water to more than 11 million people in Mexico and 4 million in the US and irrigates more than 780,000 hectares in the two countries. [24]

Snowmelt runoff (the primary source of water replenishment) has declined by 17% since 2000, but water managers in three US states and four Mexican states have been

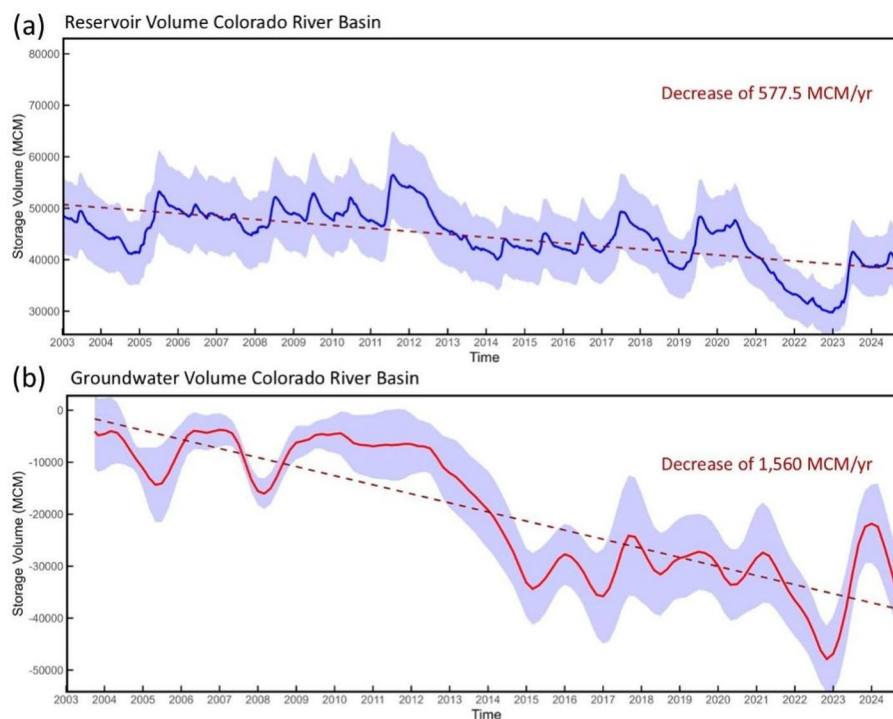


Fig. 3 Trends in **a** reservoir and **b** aquifer volume, Colorado River basin. The light shading represents uncertainties. Rapid loss of water available from reservoirs in 2011–2014 and in 2020–2022 corresponded with greatly increased groundwater pumping and aquifer depletion during 2012–2015 and 2021–2022, respectively

unable to constrain water consumption to maintain balance with this diminished replenishment [25]. As a result, both reservoirs and aquifers have been heavily depleted (Fig. 4); reservoir storage declined by 15% during 2003–2024, at an average rate of -255.4 MCM/year. Aquifer declines were much (10x) more severe, at an average of -2620 MCM/year. River outflows at the basin outlet near Brownsville, Texas have also decreased at an average rate of -29.2 MCM/year.

Total direct human consumption in the basin has been estimated at 6,034 MCM/year [25]. A comparison of the volumetric change in reservoirs, aquifers, and river outflows in the basin ($-2,904.6$ MCM/yr) with human consumption yields an IWSS of -48% , indicating highly unsustainable overconsumption. Climate scientists have projected additional decreases of 16–28% in water availability over the next half-century [26], suggesting the need for much greater reductions in consumptive use in coming decades to rebalance consumption with water availability.

2.3 Great Salt Lake basin

The Great Salt Lake is the largest saline lake in North America and eighth largest in the world. It is an endorheic lake (no outlet), receiving inflows from more than 54,000

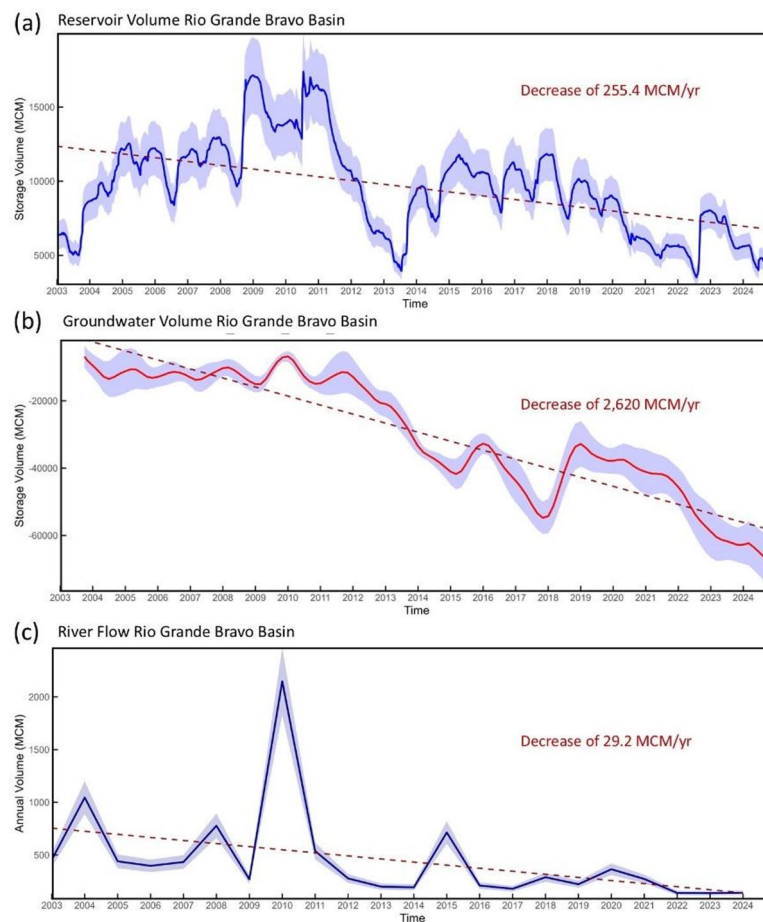


Fig. 4 Trends in **a** reservoir, **b** aquifer, and **c** river flow volumes, Rio Grande-Bravo basin. The light shading represents uncertainties. Large decreases in reservoir volume during 2011–2013 and 2018–2024 corresponded with greatly increased groundwater pumping and aquifer depletion during 2011–2015 and 2019–2024, respectively

square kilometers including the Wasatch Mountain Range, where much of the basin's water replenishment comes.

in the form of more than 12 m of annual snowfall on average. The lake reached its highest.

level in more than a century in 1987 but has been dropping by 0.1 m per year, on average, since that time due to a combination of water consumption for agricultural, industrial, and urban uses, as well as reduced inflows due to climate warming. [27]

Reservoir volumes have been increasing since 2003 by an average of +40.8 MCM/year but these increases are more than offset by groundwater declines of −340 MCM/year and river outflows that have been decreasing by −87.6 MCM/year, which is the ultimate cause of lake level declines (Fig. 5).

Total direct human consumption in the basin has been estimated at 2,280 MCM/year [27]. A comparison of the volumetric change in reservoirs, aquifers, and river outflows in the basin (−386.8 MCM/yr) with human consumption yields an IWSS of −17%, indicating unsustainable overconsumption.

2.4 Central Valley of California

The Central Valley of California is one of the most productive agricultural regions in the world. The broad flat valley bottom is roughly 80 km in width and 640 km in length,

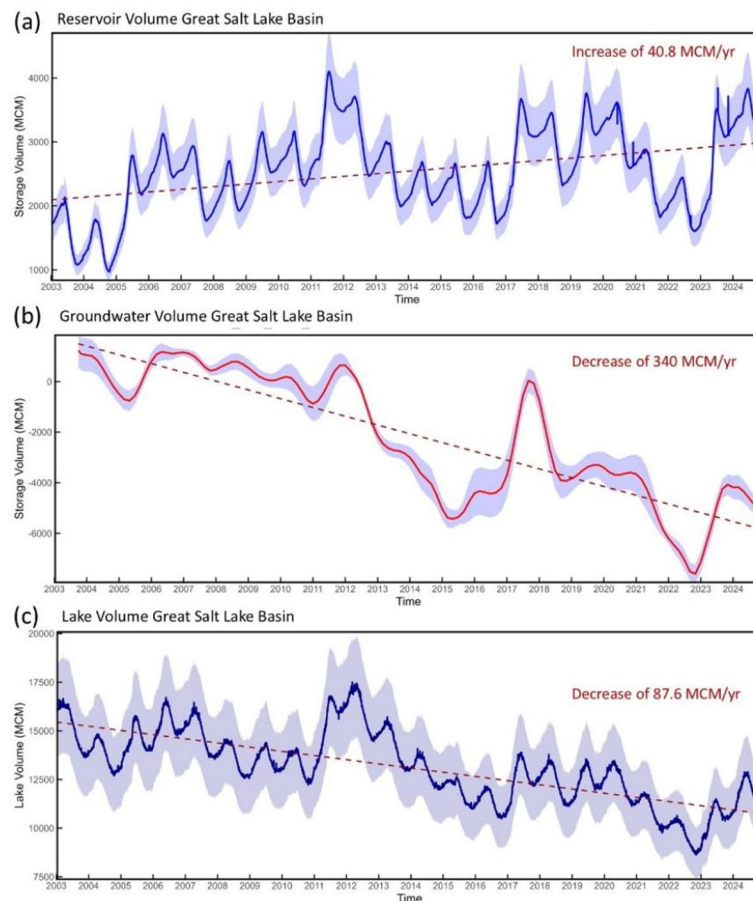


Fig. 5 Trends in **a** reservoir, **b** aquifer, and **c** lake volumes, Great Salt Lake basin. The light shading represents uncertainties. Change in lake volume is used as a proxy for declines in river flows into the lake from multiple rivers

through which flows the Sacramento and San Joaquin rivers that eventually discharge into the San Francisco Bay. Virtually all water consumption in the valley is associated with irrigated agriculture, primarily to grow fruit and nut trees, rice, cotton, grain crops and hay.

Groundwater overdraft has been a major concern in this valley since the 1920s, in part due to excessive land subsidence that has reached 9 m in some areas [28]. Serious groundwater declines have been well documented [29, 30], and have continued through our study period, estimated at $-1,750$ MCM/year (Fig. 6). Reservoir depletion is occurring at the rate of -75.3 MCM/year. River outflows have also been declining at the rate of -17.6 MCM/year.

Total direct human consumption in the basin has been estimated at 32,934 MCM/year [31]. A comparison of the volumetric change in reservoirs, aquifers, and river outflows in the basin (-1842.9 MCM/yr) with human consumption yields an IWSS of -6% , indicating unsustainable overconsumption.

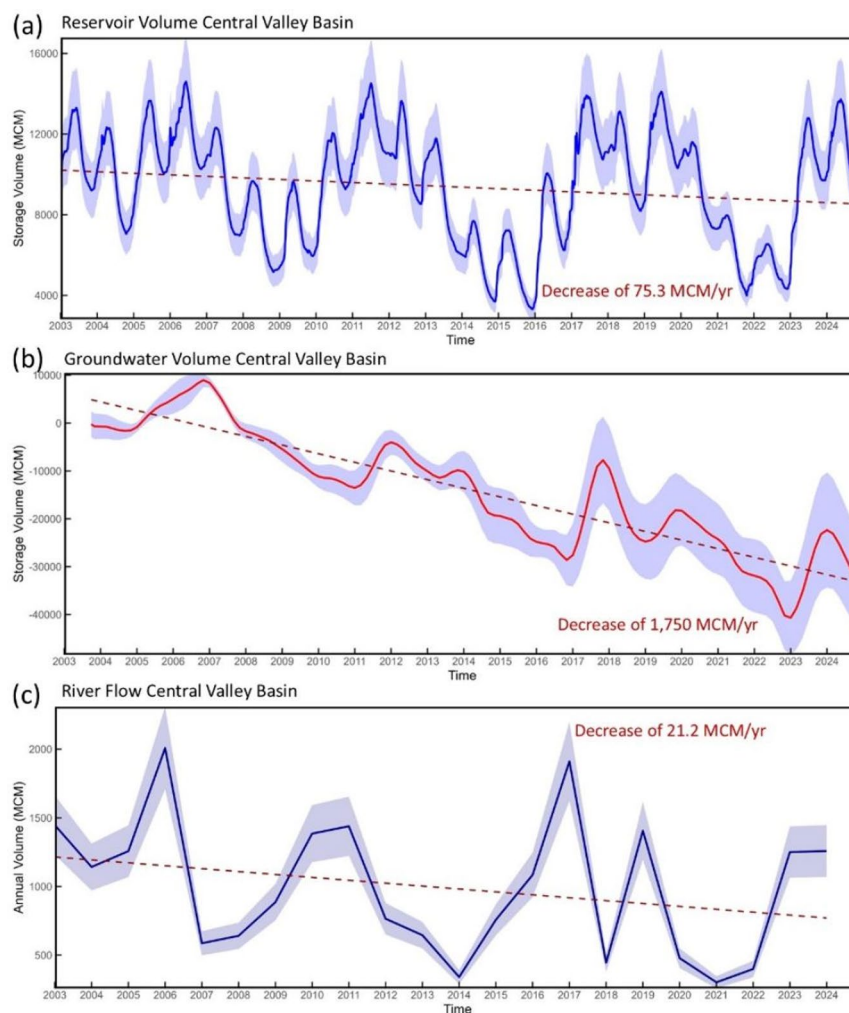


Fig. 6 Trends in **a** reservoir, **b** aquifer, and **c** river flow volumes, Central Valley of California. The light shading represents uncertainties

2.5 Snake River basin

The Snake River basin in Idaho is the largest tributary of the Columbia River system, draining 280,000 square kilometers. Water consumption is strongly dominated by irrigated agriculture, supporting production of more than 180 different crops. [32]

Irrigated farms along the Snake River relied almost entirely upon river flows and reservoirs until the 1950s, when groundwater pumping began increasing rapidly. During our study period, both reservoir storage and river outflows increased slightly (+ 33.9 MCM/yr and +4.8 MCM/yr, respectively), but groundwater depletion is a serious problem at − 600 MCM/year (Fig. 7).

Total direct human consumption in the basin has been estimated at 5,268 MCM/year [33]. A comparison of the volumetric change in reservoirs, aquifers, and river outflows in the basin (− 561.3 MCM/yr) with human consumption yields an IWSS of − 11%, indicating unsustainable overconsumption.

2.6 Platte River basin

The Platte River is one of the most significant tributaries in the Missouri River basin, draining a large portion of the central Great Plains in Nebraska and the eastern Rocky

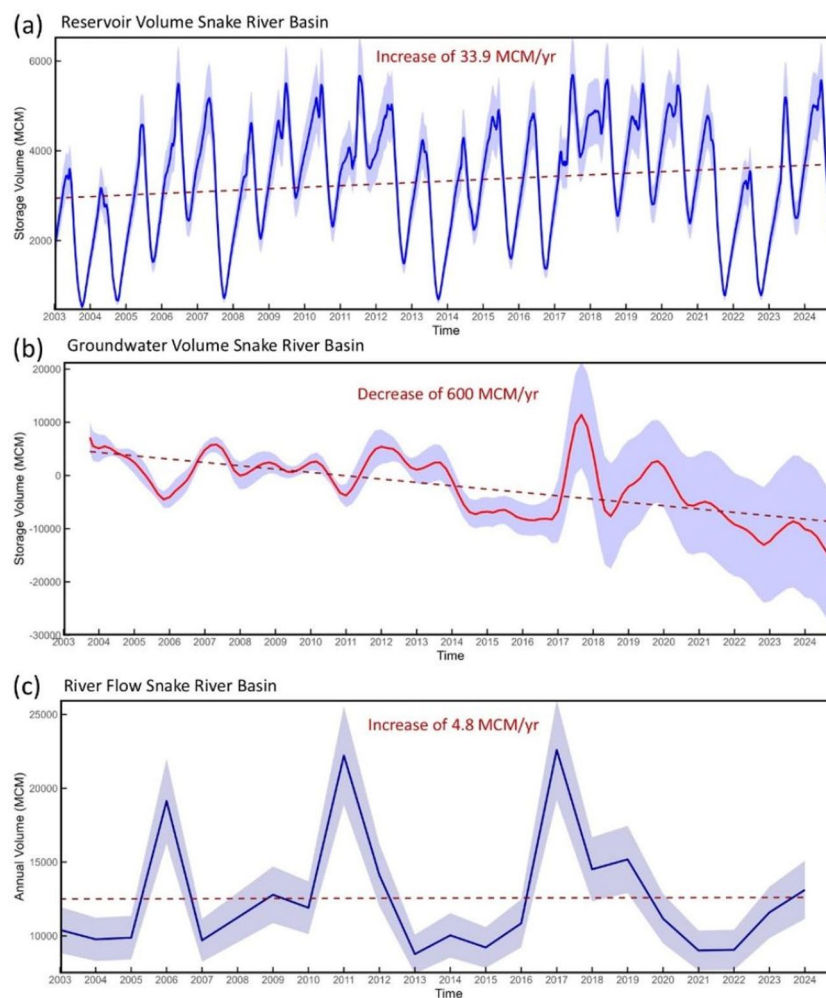


Fig. 7 Trends in **a** reservoir, **b** aquifer, and **c** river flow volumes, Snake River basin. The light shading represents uncertainties

Mountains in Colorado and Wyoming. A big concern driving many decisions about water use along the Platte River is the mandate to protect habitats of four species listed under the US Endangered Species Act: the whooping crane (*Grus americana*), piping plover (*Charadrius melodus*), interior least tern (*Sterna antillarum athalassos*), and pallid sturgeon (*Scaphirhynchus albus*). The recovery plan developed in 2006 for these species calls for river flow restoration of as much as 185 MCM/year in Nebraska [34]. This volume of water is stored in upstream reservoirs and then released to meet targeted environmental flow conditions in downstream reaches.

Implementation of the recovery plan appears to have benefitted river flows, as evidenced by the increasing trend of +115.4 MCM/year (Fig. 8). The reservoir volumes are also on an increasing trend of 46.7 MCM/year and aquifer volumes are increasing by 930 MCM/year.

Total direct human consumption in the basin has been estimated at 7,599 MCM/year [33]. A comparison of the volumetric change in reservoirs, aquifers, and river outflows in the basin (+ 1092.1 MCM/yr) with human consumption yields a IWSS of +14%, indicating sustainable consumption.

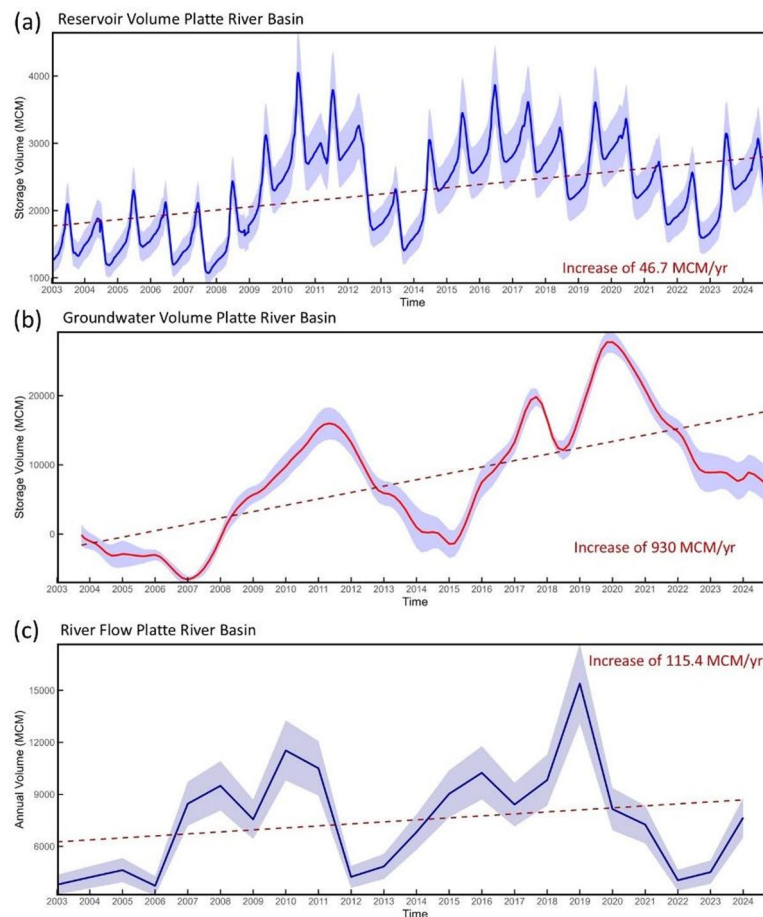


Fig. 8 Trends in **a** reservoir, **b** aquifer, and **c** river flow volumes, Platte River basin. The light shading represents uncertainties

3 Discussion

It is clear from our results that water users and managers in many basins in the western US are struggling to maintain a sustainable balance between consumptive water use and natural replenishment from snowmelt, rainfall, and aquifer recharge, particularly under the increasing influence of climate change. Five of the six case studies examined here reveal unsustainable overconsumption ranging from -6 to -48% .

It will be impossible to bring river basins within the western US back into sustainable water balance without substantial reductions in the volume of water being consumed in irrigated agriculture, which accounts for 86% of all water consumption in this region and is dominant in each of our study basins [35]. Great progress is being made in reducing the volume of water consumed in urban areas [36, 37], but municipal, commercial, and industrial water consumption pales in comparison to the volume consumed in agriculture.

There are many proven strategies for reducing irrigation needs [38] but there are very few real-world examples in which these measures have been applied at the scale needed to rebalance water budgets. Agricultural water conservation efforts are being implemented in each of the five over-drafted basins discussed here but none have yet achieved the necessary scale of water-use reduction. In the Colorado River basin, billions of US dollars have been spent paying farmers to temporarily fallow their farm fields in an effort to reduce irrigation, which accounts for 74% of direct human use [39]. In the upper Rio Grande in Colorado, farmers are charged a fee to pump groundwater and these fee revenues are used to pay other farmers to fallow farmland, while farmers in the middle Rio Grande in New Mexico are paid to fallow farmland as well [25]. Both temporary fallowing and irrigation efficiency improvement projects have been funded in the Great Salt Lake basin [27]. In the Central Valley of California, a variety of conservation investments and incentive programs have been implemented for many years [40, 41]. An aquifer management plan adopted for the Eastern Snake River Plain Aquifer called for restoration of 740 MCM/year, a level that would rebalance this hydrologic system. However, none of these efforts have yet been sufficient to stabilize water sources in these basins, although above-normal precipitation in 2022–2024 helped to temporarily stall long-term declines.

It is very important to note that our overconsumption estimates would be markedly reduced if groundwater declines were not included in our calculations. This emphasizes the critical importance of including all water sources in evaluating water-supply sustainability. Groundwater declines are easily overlooked simply because they are not visible to water users and managers, but given the often-strong interactions between groundwater and surface water conditions it is essential to view water sustainability holistically.

The Platte River basin provides a hopeful example with a positive IWSS value of $+14\%$. However, we caution that groundwater storage has been declining in this basin since 2020 (Fig. 8b), suggesting there is potential for groundwater declines to reduce river flows due to strong hydrologic connections along the Platte [42]. These recent declines also suggest a need to carefully assess year-to-year changes in addition to longer-term trends when evaluating whether individual water sources are being managed sustainably.

We have not directly addressed the implications of negative trends in water volumes for freshwater ecosystems and species. However, it is widely accepted that reduced water volumes or river flows can adversely impact ecological health, although individual

species typically respond to hydrologic changes in complex ways and with differing sensitivities [43]. While it is very important to consider these ecological impacts in assessing water-use sustainability more broadly, we suggest that an IWSS assessment can serve as a very useful complement to ecological studies including environmental flow assessments, and can provide a means for prioritization of detailed ecological assessments. We also direct readers to other papers we have cited for each of our case studies for documentation of ecological concerns in each of the six case study basins.

We have demonstrated the utility of our proposed metric for evaluating sustainability in water-supply management. We suggest that our approach offers three important benefits: (1) it enables water managers to consider all water sources in assessing risks to water supplies; (2) it is based on measurements rather than hydrologic simulation models, thereby providing higher confidence in its results; and (3) it quantifies the degree of adjustment that needs to be made to rebalance consumption with replenishment, thereby helping to scale conservation actions appropriately.

4 Methods

4.1 Estimating volumetric changes in river outflows

Annual runoff volumes were obtained from the USGS's "Water Data for the Nation" webpages [44]. Data were obtained from monitoring stations closest to each river's outflow location that included measurements for the 2003–2024 period of record. The average annual rate of change was estimated using the slopes of the linear regression lines. While the assumption of a normal distribution of residuals may be violated in some cases, we feel that the greater familiarity of linear regression methods and tools such as Excel for estimating linear trends justifies use of this statistical approach. Some analysts will prefer to use alternate methods for implementing our indicator in cases of substantial non-normality in data distribution or in the presence of severe outliers or missing values, however.

4.2 Estimating volumetric changes in reservoirs

Daily estimates of reservoir volume were obtained from multiple sources including the US Bureau of Reclamation's "Reclamation Information Sharing Environment (RISE)" webpages [45], the Natural Resources Conservation Service's "Air & Water Database Report Generator" webpages [46], the Texas Water Development Board's "Water Data for Texas" webpages [47], the International Boundary & Water Commission's "Water Data Portal" webpages [48], and personal data requests from the Salt River Project in Arizona, the Utah Division of Water Resources, the Wyoming State Climate Office, and the Big Wood Canal Company in Idaho. The average annual rate of change was estimated using the slopes of the linear regression lines.

4.3 Estimating volumetric changes in GRACE/GRACE-FO terrestrial water storage (TWS_A)

Monthly estimates of water volumes were estimated for six major basins in the Western United States over the period 2003–2024 using monthly GRACE/GRACE-FO observations. GRACE Release 06 mascon solutions were obtained from the University of Texas Center for Space Research (CSR-RL06.02 M), NASA Jet Propulsion Laboratory (JPL-RL06.1 M), and NASA Goddard Space Flight Center (GSFC-RL06v2.0 M) [19, 20, 49, 50]. Mascon products were selected due to their reduced leakage and improved effective

Table 1 Summary of IWSS calculations for six river basins. Volumes in MCM/year

Basin	Change in reservoirs	Change in aquifers	Change in river outflow	Sum of changes	Human consumption	IWSS
Colorado River	−577.5	−1,560		−2137.5	16,818	−13%
Rio Grande-Bravo	−255.4	−2,620	−29.2	−2,904.6	6,034	−48%
Great Salt Lake	+40.8	−340	−87.6	−386.8	2,280	−17%
Central Valley	−75.3	−1,750	−17.6	−1,842.9	32,934	−6%
Snake River	+33.9	−600	+4.8	−561.3	5,268	−11%
Platte River	+46.7	+930	+115.4	+1092.1	7,599	+14%

spatial resolution compared to spherical harmonic solutions. The JPL mascon data was corrected using the Coastline Resolution Improvement technique. [51]

GRACE terrestrial water storage anomaly (TWS_A) were extracted for each basin by applying basin masks to gridded data and computing area-weighted averages. All anomalies were referenced to the 2009–2014 mean period. Missing monthly GRACE observations were infilled using linear interpolation prior to time-series decomposition.

To separate long-term variability from the seasonal cycle, we applied Seasonal-Trend decomposition using LOESS (STL) to each monthly basin-mean time series (TWS_A and all component anomalies described below). STL decomposes a time series into trend, seasonal, and remainder components using an iterative, non-parametric procedure. Our primary analyses focus on the trend (long-term) component (Eq. 1; Figure S1 in supplementary file) series. [52, 53].

$$X(t) = T(t) + S(t) + R(t) \quad (1)$$

Where $X(t)$ monthly GRACE-derived time series, $T(t)$ is the trend (long-term) component, representing interannual to decadal variability, $S(t)$ is the seasonal component, capturing periodic variations, and $R(t)$ is the remainder (residual) component, which includes short-term variability and noise. Uncertainty in monthly basin-mean TWS_A was estimated from the inter-solution spread among the three GRACE mascon products as described below:

We estimated volumetric changes in groundwater storage (GWS_A) from GRACE TWS_A using a standard water-budget partitioning approach (Eq. 2; Table 1): [16, 54–56].

$$GWS_A = TWS_A - SWE_A - SWRS_A - SMS_A \quad (2)$$

where SWE_A is volumetric change in snow water equivalent, $SWRS_A$ is volumetric change in surface water reservoir storage, and SMS_A is volumetric change in soil moisture storage. All components were computed as basin-averaged monthly changes over the selected basins.

SWE_A was derived from Snow Data Assimilation System (SNODAS) [57]. We adopted a representative $\pm 15\%$ uncertainty for SWE_A , consistent with the accuracy levels reported and commonly assumed in large-scale water storage partitioning studies. [58–60]

$SWRS_A$ were computed from ground-based reservoir monitoring datasets for major reservoirs within each basin. Because most reservoir databases do not provide formal error estimates, we assigned a $\pm 15\%$ uncertainty to $SWRS_A$, following common practice in GRACE groundwater applications. [61]

SMS_A was obtained from the North American Land Data Assimilation System (NLDAS) [62] using three land-surface models: MOSAIC, NOAH, and VIC (Figure S2 in supplementary file). These models generally represent soil moisture within the upper ~2 m using 3–4 soil layers, which captures the dominant variability in near-surface soil water storage relevant for partitioning GRACE TWS_A at basin scales. Basin-mean SMS_A was computed for each model and then the mean used to estimate groundwater via Eq. (2), where error in SMS_A was estimated as the standard deviation across the three NLDAS models.

Finally, the total uncertainty in GWS_A was computed by combining component uncertainties in quadrature Eq (3) (Figure S3 in the supporting information):

$$\sigma GWS_A = \sqrt{\sigma TWS_A^2 + \sigma SWRS_A^2 + \sigma SMS_A^2 + \sigma SWE_A^2} \quad (3)$$

Groundwater storage estimates derived from GRACE/GRACE-FO should be interpreted within the limitations of the water-budget partitioning approach. Although uncertainties in the major storage components were propagated into the GWS estimates, additional uncertainty may arise from GRACE spatial resolution, limitations in modeled soil moisture and snow storage, incomplete representation of surface water storage, and potential covariance among component errors. These uncertainties may affect the magnitude of estimated groundwater changes, particularly in smaller basins; however, the use of multiple GRACE/GRACE-FO solutions and land-surface models provides a measure of the sensitivity of the results to different data products and processing approaches.

4.4 Estimating consumptive use

Estimates of direct consumptive use for human purposes for three basins were obtained from three previous papers describing the water budgets of the Colorado River [21], Rio Grande-Bravo [25], and Great Salt Lake [27]. Consumptive use estimates for the Snake River and Platte River were based on hydrologic model outputs used in a crop-shifting study as described in Richter and others (2023). [33]

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Author contributions

BDR conceived the study, assembled and analyzed data, and wrote the manuscript. KA, JSF, PC, and LM assembled and analyzed data and edited the manuscript. KA also prepared (Figs. 2–8).

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

The publication of this manuscript has been approved by all authors. *Dual publication*: Nothing in this manuscript has been previously published nor under consideration for publication elsewhere.

Competing interests

The authors declare no competing interests.

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