Satellites reveal widespread decline in global lake water storage.

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Abstract: Climate change and human activities increasingly threaten lake water resources that account for 87% of Earth's liquid surface freshwater (*1*–*3*). Yet, trends and drivers of lake water storage over decadal scales remain poorly constrained across the globe. Here, using three decades of satellite observations, climate data, and hydrologic models, we report declining storage for over 60% of both large natural lakes and reservoirs over 1992-2020. Roughly half of the net volume loss in natural lakes is attributable to unsustainable water consumption, climate warming or increasing evaporative demand with sedimentation dominating storage losses in drying reservoirs. Our findings indicate substantial human and climatic alteration of decadal lake water storage variability, underscoring the critical importance of incorporating climate adaptation and sustainable water use into water management.

One-Sentence Summary: Declining storage in two-thirds of Earth's large lakes over the past three decades is due to both human and climatic drivers.

Lakes cover 3% of the global land area (*4*), storing standing or slowly flowing water that provides essential ecosystem services of freshwater and food supply, waterbird habitat, cycling of pollutants and nutrients, and recreational services (*5*). Lakes are also key components of biogeochemical processes and regulate climate through cycling of carbon (*6*). The potential goods and services from lakes are modulated by lake water storage (LWS) (*7*), which fluctuates in response to changes in precipitation and river discharge, as well as due to direct human activities (damming and water consumption), and climate change. It is well documented that some of the world's largest lakes have recently experienced decline in water storage (*2*, *3*, *7*–*9*). However, the drivers of LWS decline have either been poorly constrained by inconsistent methods and assumptions or remain unknown for the majority of unstudied large lakes (> 100 km^2) that lack a decadal-scale LWS record (*10*). For example, recent level declines in the Caspian Sea have been primarily attributed to entirely different processes, either evaporative losses from the water body (*11*) or decreasing river discharge (*12*). Similarly, the decline of China's largest freshwater body, Lake Poyang, has been separately attributed to either the operation of the Three Gorges Dam (*9*), or natural variability (*13*). More broadly, there have been indications of global shifts in LWS over recent decades. Between 1984 and 2015, a loss of 90,000 km^2 of permanent water area was observed using satellites—an area equivalent to the surface of Lake Superior, while 184,000 km^2 of new water bodies, primarily reservoirs, were formed elsewhere (*14*). Yet, trends and drivers of global LWS remain poorly known, which impedes sustainable management of surface water resources, both now and into the future.

The estimation of trends and variability in global LWS has been complicated by modeling and observational limitations. Current global hydrologic models either neglect LWS changes (*15*) or provide over-simplified simulations using one-dimension models of lake volume changes (*16*). In-situ measurements of lakes are spatially sparse, have irregular temporal coverage, or are generally in decline (*17*). Satellites provide a crucial dimension for assessing large-scale LWS variability via repeat observations of lake areas and water levels from space. However, sensor limitations, such as coarse resolution, infrequent overpasses, large inter-track spacing, and mission gaps, prevent the direct development of a global inventory of LWS changes over time. As a result, existing global-scale studies that document lake volume changes lack the capability to attribute decadal-scale LWS variability due to limited spatial coverage (*10*, *18*, *19*) or short temporal duration (< 2 years) (*20*) or large gaps in the LWS time series (>9 years) (*21*). Using NASA's ICESat-2 satellite and a one-dimension model (assuming a constant lake area), a recent study mapped water levels and storages in 227,386 global water bodies over 2018-2020 and found that reservoirs, defined as water bodies regulated by a dam, dominated seasonal variability in global lake water storage (*20*). Given the brevity of the study period (< 2 years) and limited attribution, i.e., only separating natural lakes and reservoirs (*20*), decadal-scale LWS variability and attribution remains an open question. Another attempt combined water levels from ICESat and ICESat-2 to map LWS changes in 6,567 lakes over 2003-2020 and compared LWS changes across different climate regimes (*21*) but suffered from a 9-year discontinuity (2010-2018) in LWS time series and limited ability to capture and diagnose drivers of interannual variability and trends over the recent decades. Therefore, the human and climate change footprints on global LWS changes over decadal timescales remain critically unknown.

To address this challenge, we construct a global database of time-varying LWS (GLWS) from 1992 to 2020, and then decouple the impacts of anthropogenic and natural factors on decadal-scale variability in LWS (Fig.1). This GLWS archive consists of sub-yearly storage time series for 1,980 large water bodies, including 1,061 natural lakes (100 - 377,002 km^2) and 919 reservoirs (4 – 67,166 km^2), which account for 96% and 83% of Earth's natural lake and reservoir storage, respectively (*4*, *22*). We focus on large lakes because of the fidelity of satellite observations at this scale, their dominance on controlling total lake volume change (*8*, *20*), as well as their importance for human and wildlife populations (*23*). We leverage recent advances in both algorithms and cloud-based parallel computing to incorporate fine-resolution (30m) satellite observations (Methods). We apply a recently developed algorithm (*24*) to construct time-varying water areas for these lakes using a total of 248,649 Landsat scenes. We estimate lake volume variability by combining water areas with water surface elevation measurements from satellite altimeters, including CryoSat-2, ENVISAT, ICESat, ICESat-2, Jason series 1-3, SARAL, and Sentinel 3. On average, we derive six estimates per year over the 28-year study period for each studied water body. We further provide a global-scale attribution of volume trends in natural lakes using a statistical-learning framework that incorporates major natural and anthropogenic drivers estimated from global climate data and hydrologic models. For reservoirs, we aggregate impacts of recent dam construction and subsequent reservoir infilling using newly compiled global dam and reservoir inventories (*26*), as well as sedimentation using in-situ sediment surveys and upscaling methods. Finally, we isolate lake storage trends between arid and humid regions and quantify the numbers of local populations subject to lake water losses.

Global LWS trends and drivers

We identify widespread decline in global LWS over the past 28 years. Two-thirds of large lakes show a drying trend (Fig. 1). LWS loss prevails across major global regions including western Central Asia, the Middle East, western India, eastern China, northern and eastern Europe, Oceania, the conterminous United States, northern Canada, southern Africa, and most of South America. Globally, LWS shows a net decline at a rate of -22.34 ± 3.54 Gt yr^{-1} (Fig. 2A and 2D), or by 625.52 km^3 in accumulative volume—equivalent to the total water use in the US for the entire year of 2015 or 17 times the volume of Lake Mead, the largest reservoir in the United States.

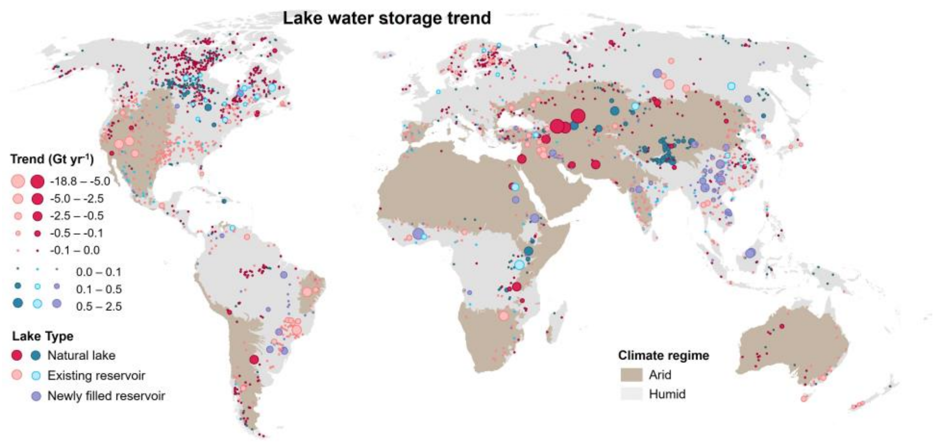

Fig. 1. Widespread storage decline in large global lakes from October 1992 to September 2020. Lake water storage (LWS) trends for 1,061 natural lakes (dark red and dark blue dots) and 919 reservoirs (light red and light blue dots). Note that recently filled reservoirs after 1992 are denoted as light purple dots. Classification of arid regions includes arid, semi-arid, and semi-humid basins, using the aridity index (ratio of mean annual precipitation to mean annual potential evapotranspiration—Methods).

Globally, natural lake volume declined at a rate of -26.74 ± 1.64 Gt yr^{-1}, of which 42% is attributable to direct human activities or changes in temperature and potential evapotranspiration (PET), i.e., evaporative demand (Fig. 2G). Over 70% of the total decline stems from the 26 largest losses (> 0.1 Gt yr^{-1}, $p < 0.05$) (Fig. 3A). Unsustainable water consumption dominates the observed drying of the Aral Sea (-6.59 Gt yr^{-1}) in Central Asia, Lake Mar Chiquita (-0.75 Gt yr^{-1}) in Argentina, the Dead Sea (-0.63 Gt yr^{-1}) in the Middle East, and the Salton Sea (-0.11 Gt yr^{-1}) in California. Increasing temperature and PET led to the complete disappearance of Lake Good-e-Zareh (-1.15 Gt yr^{-1}) in Afghanistan, Toshka lakes (-0.40 Gt yr^{-1}) in Egypt, and marked drying of Lake Kara-Bogaz-Gol (-1.27 Gt yr^{-1}) in Turkmenistan, Lakes Khyargas (-0.35 Gt yr^{-1}) and Uvs (-0.20 Gt yr^{-1}) in Mongolia, Lake Zonag (-0.26 Gt yr^{-1}) in China, and Lake Lama (-0.21 Gt yr^{-1}) in Russia. The remaining change is primarily attributable to changes in precipitation and runoff, including the Caspian Sea (-18.80 Gt yr^{-1}), Lake Urmia (-1.05 Gt yr^{-1}) in Iran, the Great Salt Lake (-0.29 Gt yr^{-1}) in the United States, Lake Poyang (-0.13 Gt yr^{-1}) in China, Lake Titicaca (-0.12 Gt yr^{-1}) on the border of Bolivia and Peru, and others, which largely agrees with existing studies (*8*, *12*, *13*, *27*). while a recent study suggests the drying of Lake Urmia was primarily attributed to human activities (*28*), we find that naturalized flows explain 67% of the variance in the annual mean lake volume compared with 52% explained by human water consumption. Thus, the decline of Lake Urmia is likely a concurrent result of both reduced natural flows and human activities. Arctic lakes are mostly in decline due to a combination of changes in precipitation, runoff, temperature and PET (Fig. 3A), which are likely a concurrent result of natural variability and climate change. Globally, temperature-and-PET changes dominate water loss in 23% of drying lakes ($p < 0.05$) (Fig. 3A). Approximately one-third of the total decline in all drying lakes is offset by precipitation-and-runoff-driven storage increases elsewhere, largely in remote areas such as the Tibetan Plateau, Northern Great Plains, and Great Rift Valley (Fig. 3B).

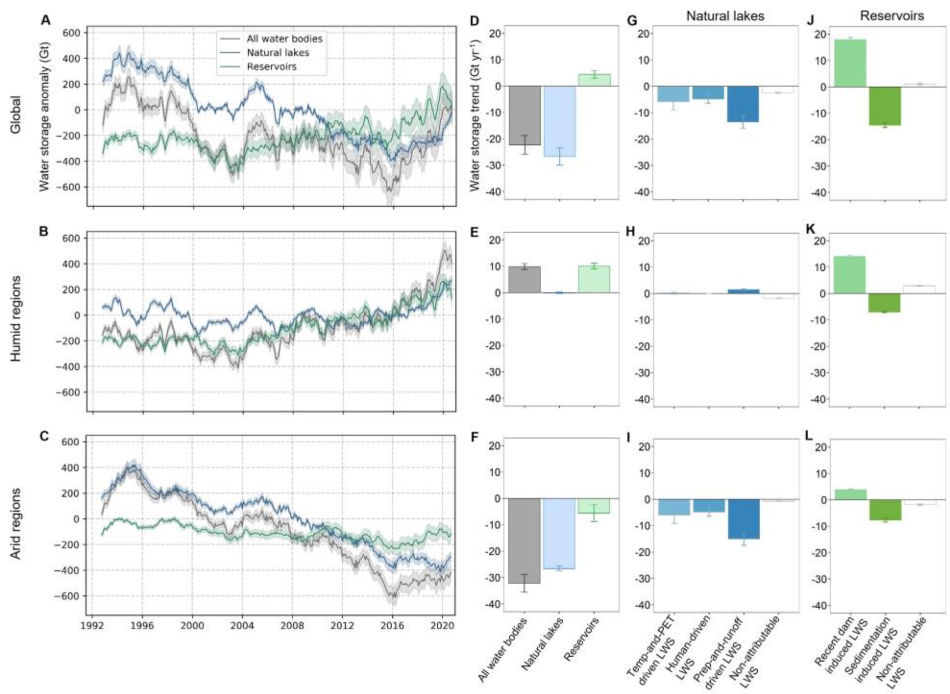

Fig. 2. Time series and drivers of global lake water storage, October 1992 to September 2020. A-F, time series and trends for aggregate storage anomalies for each type of water body for global, humid, and arid regions, respectively. **G-L**, attribution of storage trends in natural lakes and reservoirs. Temp, Prep, and PET stand for temperature, precipitation, and potential evapotranspiration, respectively. The shading denotes the LWS uncertainties in all water bodies (grey shading), natural lakes (blue shading), and reservoirs (green shading) at a 95% confidence interval. The error bars show the aggregate uncertainty in LWS trends at a 95% confidence interval. For natural lakes, 40% of the net global decline is attributable to human activities and increasing temperature and potential evapotranspiration. Recent dam construction, largely from humid basins, supported the net increase in global reservoir storage, although over 80% of the increased storage in recently filled reservoirs is offset by sediment-induced storage loss in existing reservoirs.

Two-thirds of all large reservoirs show a storage decline, although reservoirs show a net global increase at a rate of 4.41 ± 1.43 Gt yr^{-1}, owing to 184 (20%) recently filled reservoirs. Storage declines in existing reservoirs, i.e., filled before 1992, are seen in most global regions. Global storage decline in existing reservoirs (-13.50 ± 1.13 Gt yr^{-1}) can be largely attributed to sedimentation (Fig. 2J), which is consistent with observations of substantial storage decline in US reservoirs due to sedimentation (*36*). Globally, sediment-induced storage loss offsets more than 80% of the increased storage from new dam construction (Fig. 2J). Our finding suggests that sedimentation is the primary contributor to the global storage decline in existing reservoirs and has a larger impact than hydroclimate variability, i.e., droughts and recovery from droughts (ref). Recent droughts may have contributed to reservoir storage declines, particularly in the southwestern United States (*29*), eastern and southern Brazil (*30*), the Middle East (*31*), southern India (*32*), eastern and southeastern Asia (*33*), eastern Oceania (*34*), and most of Europe (*35*). However, drought impacts on reservoir LWS have been partially offset by wetting trends elsewhere (*12*), such as the headwaters of the Nile River, southeastern Canada, and Mexico (Fig. 1).

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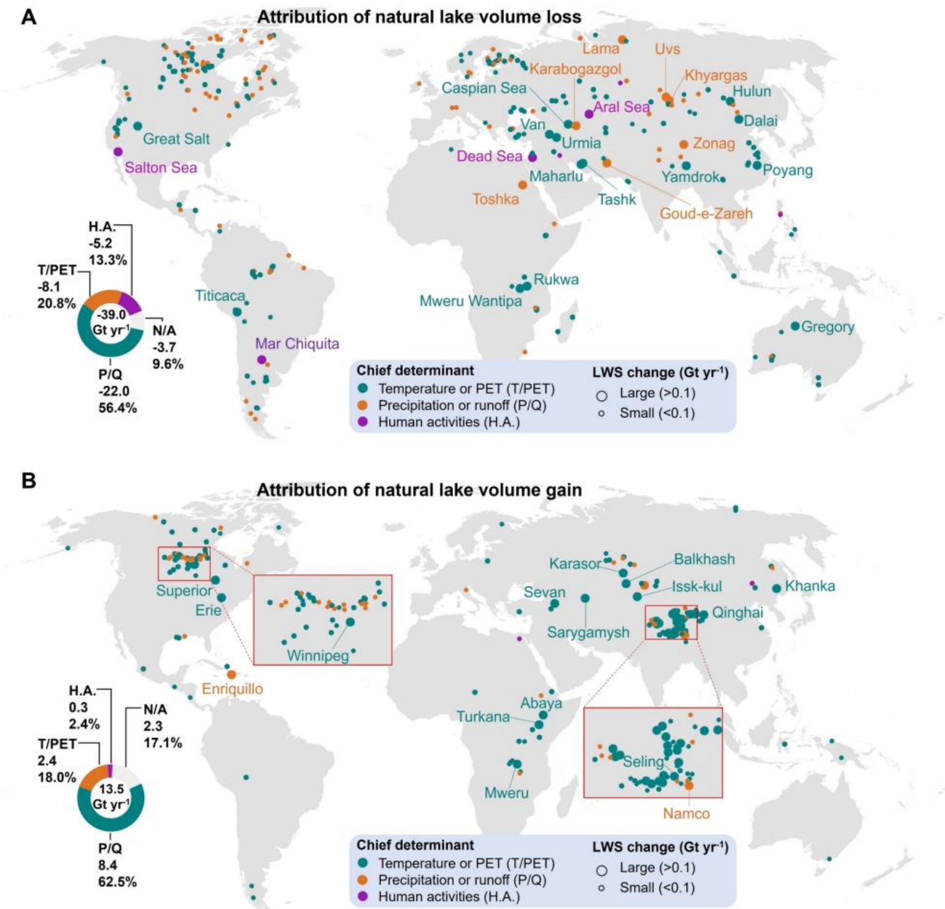

Fig. 3. Attributions of significant volume changes (p < 0.05) in natural lakes. (**A**) Chief determinants for volume losses. (**B**) Chief determinants for volume gains. The inset pie charts show the aggregate impact (by magnitude) of each determinant based on relative contributions. For clarity, lake volume changes that are not significantly attributable (N/A) are not shown in panels (**A)** and (**B),** but their proportions are included in the inset.

LWS trends in arid and humid regions

Arid regions experienced a net storage decline for both natural lakes and reservoirs at a rate of -26.63 ± 3.22 Gt yr^{-1} and -5.58 ± 0.92 Gt yr^{-1}, respectively. Over 70% of the total LWS loss in arid regions stemmed from basins with either a drying climate or unsustainable human water consumption or both, such as in the Aral Sea Basin and the Colorado River Basin (Fig. 4). About 23% of the loss is attributable to changes in temperature and PET and another 18% is explained by human activities (Fig. 2I). Approximately, 60% of water bodies in arid regions show a significant water loss ($p < 0.05$). One-quarter of the water losses in natural lakes were dominated by changes in temperature and PET or human activities, while another 43% of the water losses were primarily attributable to reduced natural flows. Storage declined ($p < 0.05$) in over two-thirds of reservoirs in arid regions. The net reservoir storage loss was mostly attributed to sedimentation (Fig. 2L), although droughts likely aggravated reservoir storage losses, such as in the Colorado River Basin and the Tigris & Euphrates Basin (*31*, *37*).

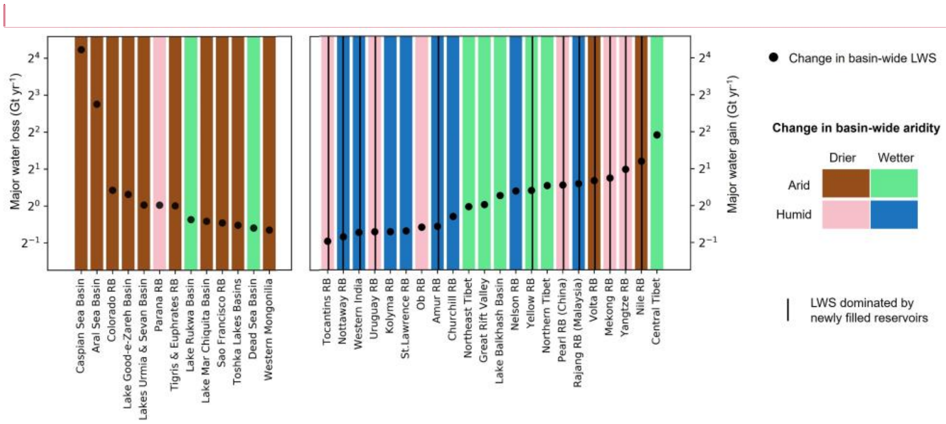

Fig. 4. Major losses and gains in basin-wide lake water storage (greater than 0.5 Gt yr^{-1}). Bar colors represent the trending direction in aridity in arid and humid basins. The vertical line through a bar indicates basins where the LWS trend is dominated by recently filled reservoirs. Note that major losses are primarily found in arid basins that are getting drier and major gains in humid basins are mostly due to recent reservoir filling.

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Storage increase in newly filled reservoirs drives a net LWS gain in humid regions at a rate of 9.88 ± 1.15 Gt yr^{-1}, although over 70% of the remaining water bodies show a storage decline. More than 85% of the newly filled reservoirs are concentrated in a few basins with recent dam construction boom including the Nile, Yangtze, Mekong, Volta, Rajang, Pearl, Yellow, Amur, Uruguay, Tocantins, and Nottaway River Basins, as well as western India (Fig. 4). About 60% of these regions experienced a drying climate during the study period, suggesting human activities partially reversed the negative impact of climate on basin-wide surface water storage by impounding more water in reservoirs. Beyond these dam-construction hotbeds, reservoir storage is mostly in decline (Fig. 1). Most natural lakes are also in decline in humid regions, including high latitudes and the tropics (Fig. 1). However, these natural lake volume losses are offset by precipitation-and-runoff-driven LWS gains in the northern Great Plains and the Laurentian Great Lakes of North America (Fig. 3B).

Up to 1.9 billion people (roughly one-quarter of the global population in 2020) live in basins with large water bodies experiencing significant water storage losses ($p < 0.05$) (Fig. 5). Many of these lakes have been acknowledged as important sources of water and energy (hydropower) (*22*) or listed among Ramsar sites of International Importance (*38*). About 23%, 7%, and 15% of the global population reside in basins experiencing freshwater decline, environmental degradation, and energy reduction associated with decreasing LWS, respectively (Fig. 5). We note that the population numbers are only estimates of potential impacts on lake basin residents who are likely the most vulnerable to lake water loss (refs). In line with the UN's projection of two-thirds of the global population facing water shortage by 2025 (*39*), our estimates indicate water shortage related exclusively to populations living in basins with large lakes could potentially impact up to one-quarter of the global population, even though we did not account for remotely affected populations, such as those relying on virtual water trade from the affected regions. For arid regions, basins experiencing freshwater decline have the highest number (26%) of residents, followed by energy reduction in basins resided by 18% of the population, and environmental degradation in basins resided by 11% of the population. Despite

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Al-Weshah, R.A., 2000. The water balance of the Dead Sea: An integrated approach. Hydrol. Process. 14, 145–154.

the net reservoir storage increase in humid regions, about 22% of the population are facing freshwater loss and about 13% are facing energy reduction in their residing basins, indicating that the benefits of increased reservoir storage are not equally distributed.

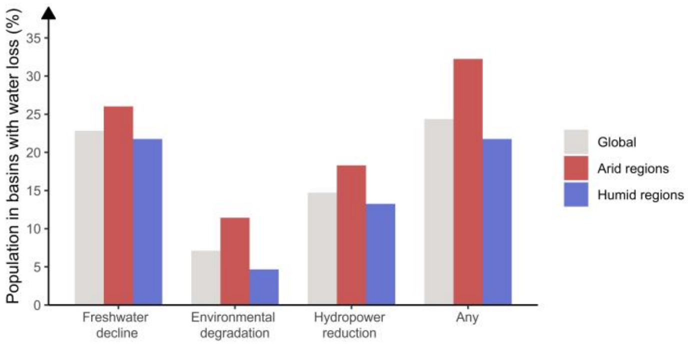

Fig. 5. Percentages of the global population residing in basins experiencing lake water loss (*p* < 0.05). Impacted sectors associated lake water loss are freshwater decline, environmental degradation, and hydropower energy reduction. Overall, over one-fifth of the global population live in basins with lake water loss in both arid and humid regions.

Discussion

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We leveraged three decades of fine-resolution satellite observations to map long-term global LWS variability, finding evidence of widespread decline in global LWS with almost half of the large water bodies (49%) exhibited a significant drying trend. One-fourth of the significant water losses ($p < 0.05$) in natural lakes were dominated by human activities or changes in temperature and PET which are primarily driven by climate change (refs). Before our study, most of these human and climate change footprints were either unknown, such as the desiccations of Lake Good-e-Zareh in Afghanistan and Lake Mar Chiquita in Argentina, or known only anecdotally, as in northern Eurasia and Canada. These water losses impact both the water and carbon cycles. For example, Arctic lakes are drying partially as a result of changes in temperature and PET (Fig. 3A), which is in line with the broader climate change pattern with

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Liu, J., Zhang, J., Kong, D., Feng, X., Feng, S., Xiao, M., 2021. Contributions of anthropogenic forcings to evapotranspiration changes over 1980–2020 using GLEAM and CMIP6 simulations. J. Geophys. Res. Atmos. 126, e2021JD035367

increasing evaporative loss due to rising lake temperature and decreasing lake ice (*40*, *41*). Changes in runoff could be in part caused by climate change through increasing evaporation (refs). Assuming runoff-driven water loss in each lake is partially attributed to climate change, 48% of the drying lakes ($p < 0.05$) were at least partially influenced by climate change as their water losses were dominated by changes in temperature, PET, or runoff (fig. S7). Widespread LWS decline, particularly along with rising lake temperature, could reduce the amount of absorbed carbon dioxide and increase carbon emissions to the atmosphere given that lakes are hotspots of carbon cycling (*6*, *42*). Increasing lake water storage could also be in part impacted by climate change, particularly in the Tibetan Plateau where glacier retreat and permafrost thawing partially led to the alpine lake expansion (refs).

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Miller, J.R., Russell, G.L., 1992. The impact of global warming on river runoff. J. Geophys. Res. Atmos. 97, 2757–2764.

Commented [FY9]: Wang, J., Song, C., Reager, J.T., Yao, F., Famiglietti, J.S., Sheng, Y., MacDonald, G.M., Brun, F., Schmied, H.M., Marston, R.A., Wada, Y., 2018. Recent global decline in endorheic basin water storages. Nat. Geosci. 11, 926–932.
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Our findings suggest that drying trends worldwide are more extensive than previously thought (*8*, *12*, *21*). Luo *et al.* (*21*) reported a net global increase in natural lake storage at a rate of 16.12 Gt yr^{-1} and that most of the global lakes in humid regions gained water storage whereas lakes in arid regions with high human water stress were generally in decline over 2003-2020. While we confirm a “dry-get-drier” pattern in LWS, our findings also show widespread LWS decline in the humid tropics and high latitude regions over the last three decades, as well as a net global decline (-26.74 ± 1.64 Gt yr^{-1}) in natural lake storage. This contrast indicates that extrapolating the trends inferred from a brief time series could be problematic, suggesting the necessity for long-term observations. For example, Luo *et al.* (*21*) concluded that Amazon lakes are largely expanding by comparing LWS changes between two short periods (2003-2009 and 2018-2020). By contract, the vast majority of Amazon lakes in our study show a decreasing LWS trend because our detailed multi-decadal LWS time series fully capture the impacts of major droughts during the early 2000s, 2010 and 2015. More broadly, our finding indicates that an intensified water cycle in a warming climate (*43*) may not result in increased water storage in humid regions, in part due to increasing land ET (*44*) and potentially longer drought recovery times (*45*). The continued observations from ongoing and new satellites, in particular the Surface Water and Ocean Topography (SWOT) mission (planned to launch in 2022), will be useful to extend the LWS trends observed here and enable longer-term assessments of the interactions among LWS, the water cycle, and climate change.

This global-scale attribution of LWS trends has important implications for water resource management. Sedimentation dominates the water loss in existing reservoirs, which suggests our heavily reliant reservoirs will become less reliable for freshwater and hydroelectric energy supply because of aging reservoirs. Nearly half of the net loss in natural lake volume (40%) is attributable to human activities or increasing temperature and PET, indicating that any recovery of water storage in these lakes could require substantial management efforts. Our findings are broadly consistent with existing studies (*3*, *28*, *46*) on human footprints on the Aral Sea, Dead Sea, and Lake Urmia, but also reveal additional undocumented human-driven LWS losses in other large lakes, such as the Salton Sea in California and Lake Chiquita in Argentina. The strongest attribution of human activities to LWS losses generally occurred in basins that were getting drier. This suggests that under conditions of declining precipitation, more intensive human-water withdrawal from rivers led at least partially to the desiccations of closed lakes. We detect that increasing temperature and PET is the chief determinant of water loss in 23% of drying natural lakes, a cautionary finding for a projected warmer future, underscoring the importance of accounting for climate adaptation within future surface water management.

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Author contributions F. Y. conceptualized the project. F.Y., J. W., J. C., and M. B. estimated and analyzed the water storage variability and trends. F. Y., B. R., and B. L. developed the statistical models. F. Y. and B. R. estimated the sediment-induced storage loss in reservoirs. F. Y. evaluated the impacts of drying lakes on population with inputs from B. L., B. R., and Y. W. F. Y. conducted the validation. F. Y. performed the visualization with inputs from B. L., J. W., and Y. W. F. Y. wrote the manuscript with inputs from B. L., B. R., J. W.. All authors read and commented on drafts of this paper.

Competing interests The authors declare no competing interests.

Data availability

The Landsat images, including Landsat 5 Thematic Mapper, Landsat 7 Enhanced Thematic Mapper-plus, and Landsat 8 Operational Land Imager, are available from the US Geological Survey at http://earthexplorer.usgs.gov and the Google Earth Engine platform at https://earthengine.google.com. ICESat and ICESat-2 data are available from the National Snow and Ice Data Center (NSIDC) at https://nsidc.org/data. Water levels derived from ICESat-2 are available at https://doi.org/10.5281/zenodo.4489056. Water level products from radar altimeters can be downloaded from the Hydroweb at http://hydroweb.theia-land.fr, the Database for Hydrological Time Series of Inland Waters (DAHITI) at https://dahiti.dgfi.tum.de/en, and the USDA Global Reservoir and Lake Monitor database at https://ipad.fas.usda.gov/cropexplorer/global_reservoir. The CryoSat-2 data are available from the European Space Agency (ESA) at https://earth.esa.int/eogateway/catalog/cryosat-products. The Global Reservoir Bathymetry Dataset can be downloaded from https://dataverse.tdl.org/dataset.xhtml?persistentId=doi:10.18738/T8/TO5HJG. The Global Surface Water (GSW) dataset is available from https://global-surface-water.appspot.com/ and the Google Earth Engine platform at https://earthengine.google.com. Reservoir sedimentation survey data from the U.S. Army Corps can be accessed at https://water.usace.army.mil/ and https://nicholasinstitute.duke.edu/reservoir-national-trends/sediment/. USGS gauge data can be downloaded from https://waterdata.usgs.gov/nwis/, U.S. Army Corps gauge data can be downloaded from https://water.usace.army.mil/ and https://nicholasinstitute.duke.edu/reservoir-data/, California Department of Water Resources gauge data can be downloaded from https://cdec.water.ca.gov/, gauge data from Texas Water Development Board can be downloaded from https://waterdatafortexas.org/reservoirs/statewide, gauge data from Spain can be downloaded from https://ceh.cedex.es/anuarioaforos/afo/embalse-nombre.asp, and gauge data from Bureau of Meteorology in Australia can be downloaded from http://www.bom.gov.au/waterdata/. The HydroLAKES database can be downloaded from https://www.hydrosheds.org/page/hydrolakes. The Georeferenced global dam and reservoir dataset (GeoDAR) can be downloaded from https://doi.org/10.6084/m9.figshare.13670527. The database of Roller-Compacted Concrete (RCC) dams can be accessed at http://www.rccdams.co.uk/. The Global Lake area, Climate, and Population (GLCP) dataset can be downloaded at https://portal.edirepository.org/nis/mapbrowse?packageid=edi.394.4. The HydroSHEDS dataset can be downloaded from https://hydrosheds.org/page/overview. The Climatic Research Unit (CRU) data are available from https://crudata.uea.ac.uk/cru/data/hrg/. ECMWF Reanalysis v5 (ERA5) data are available from https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5. Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2) are available from https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/. Multi-Source Weighted-Ensemble Precipitation (MSWEP) are available from http://www.gloh2o.org/mswep/. Global Historical Climatology Network data are available from https://www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-monthly. Global Land Evaporation Amsterdam Model (GLEAM) data are available from https://www.gleam.eu/. Global Reach-scale A priori Discharge Estimates for SWOT (GRADES) dataset can be downloaded from http://hydrology.princeton.edu/data/mpan/GRFR/discharge/daily/. The reconstructed human water use data derived from four global hydrologic models can be downloaded from https://zenodo.org/record/1209296#.YZPcr2DMKM8. The water body masks delineated from the GSW dataset, lake volume time series derived from Landsat images and satellite altimeters, lake volume trend estimates, and all validation analyses are available on the zenodo data repository no later than upon publication.

Code availability

R scripts that were used to process hydroclimate and human water use data, to derive water levels from ICESat and ICESat-2, to construct lake water storage time series, to estimate the mean rate of sedimentation in reservoirs, to estimate trends in lake water storage and basin aridity, to conduct validation, to construct regression model ensemble, and to estimate affected population, is available on the CodeOcean at https://codeocean.com/capsule/9674488. JavaScript scripts for mapping water areas from Landsat images and IDL Scripts for processing CyoSat-2 data are available in the Auxiliary Supplementary Materials.

Supplementary Materials

Materials and Methods
References (*47-79*)
Figs. S1 to S9