Science Bulletin 69 (2024) 2179–2182

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

Short Communication

Emerging global reservoirs in the new millennium: Abundance, hotspots, and total water storage

Chenyu Fan [a,b], Chunqiao Song [a,b,c,*], Jida Wang [d,e], Yongwei Sheng [f], Yaling Lin [a,b], Chunyu Yuan [a], Md Safat Sikder [d], Jean-François Crétaux [g], Kai Liu [a,c], Tan Chen [a], Fanxuan Zeng [a], Linghong Ke [h,i]

[a] Key Laboratory of Watershed Geographic Sciences, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] University of Chinese Academy of Sciences, Nanjing (UCASNJ), Nanjing 211135, China
[d] Department of Geography and Geographic Information Science, University of Illinois Urbana–Champaign, Urbana IL 61801, USA
[e] Department of Geography and Geospatial Sciences, Kansas State University, Manhattan KS 66506, USA
[f] Department of Geography, University of California, Los Angeles CA 90095, USA
[g] Laboratoire d'Études en Géophysique et Océanographie Spatiales (LEGOS), CNES-IRD-CNRS-UT3, Université de Toulouse, Toulouse 31401, France
[h] College of Hydrology and Water Resources, Hohai University, Nanjing 210098, China
[i] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, China

ARTICLE INFO

Article history:
Received 22 August 2023
Received in revised form 22 March 2024
Accepted 26 March 2024
Available online 23 April 2024

Dams and reservoirs play an essential role in regulating and managing water resources. Since the middle of the 20th century, the growing demand for water and hydropower has led to an unprecedented boom in reservoir construction worldwide [1,2]. Meanwhile, reservoir construction has also resulted in a variety of ecological and socioeconomic impacts [3–5]. Reservoirs transform natural flow regimes into conditions favored by human demand. The associated flow regulations, especially in reservoirs constructed in recent decades (e.g., after 2000) with greater seasonal variability [6,7], represent a strong human-induced alteration of the hydrologic cycle. As reservoir construction continues to boom in many parts of the world, an up-to-date and open-access inventory of reservoirs worldwide remains critically desired.

There have been several open-access global datasets that inventory reservoir locations and properties. Some of the most comprehensive ones are the Global Reservoir and Dam database (GRanD) [8], the Georeferenced global Dams And Reservoirs (GeoDAR) [9], and the Global Dam Tracker (GDAT) [10] (albeit GDAT provides no reservoir polygons). These datasets were largely compiled using dam registers from regional water agencies, intergovernmental organizations (e.g., the United Nations AQUASTAT), and/or non-governmental international agencies (e.g., the International Commission on Large Dams (ICOLD)). Completeness of the existing datasets, therefore, depends on the integrity and up-to-dateness of the source registers. While the source registers may document historical reservoirs well, it is more challenging to document newer reservoirs as thoroughly because there is usually a latency between dam construction and the update of registration, in addition to data opaqueness preventing timely access to the information about new reservoirs. These limitations imply that the abundance of recently constructed reservoirs is likely under-documented by the existing reservoir datasets and that there is a pressing need for systematically mapping newer reservoirs through a method that is not contingent on the quality of the available registers. That is, for reservoirs constructed after 2000, there is a potential for higher missing proportions within the existing dam and reservoir datasets. In addition, existing studies are still very restricted in understanding the contribution of new reservoirs to terrestrial water storage on a global scale. There is an evident gap in accurately quantifying the impact of newly constructed reservoirs on the global hydrological cycle, particularly in terms of their role in modulating terrestrial water storage dynamics.

To fill this gap, we here present a global reservoir inventory of the post-2000 impoundment (hereafter "GREI-p2k") using satellite remote sensing products. GREI-p2k consists of the maximum water extent of each detected post-2000 reservoir larger than 0.50 km^2 (considering the robustness of reservoir identification due to the remote sensing data resolution), together with the reservoir storage capacity. The primary source data for reservoir detection and mapping are the Global Surface Water (GSW) database [11] and

* Corresponding author.
E-mail address: cqsong@niglas.ac.cn (C. Song).

https://doi.org/10.1016/j.scib.2024.04.043

the Global Land Analysis and Discovery (GLAD) database [12]. Here, the identification of new reservoirs depends on the judgments of inundation frequency contrasts between the two epochs of before and after damming (1984–1999 and 2000–2020) based on the GSW Occurrence Change Intensity (OCI) data, and this provides an essential rationale for establishing the year of 2000 as the baseline of new reservoirs. The storage capacity of each post-2000 reservoir was estimated using NASADEM [13], which depicts under-water topography in early 2000 (see Supplementary materials). In addition, we identify hotspots of newly impounding reservoirs and discuss the potential driving forces from the perspective of water policies. Notably, the GREI-p2k data will be publicly available (https://doi.org/10.57760/sciencedb.15520). GREI-p2k may provide a comprehensive view of the accumulative distribution of terrestrial water storage through the construction of reservoirs after 2000. The endeavor represents a significant advancement in the fields of reservoir mapping and water resource management.

We map 6,760 post-2000 reservoirs (Fig. S1 online), with a total water area of 53,183.90 km^2 and a total reservoir storage capacity of 1,287.69 km^3, of which 139 reservoirs have a storage capacity greater than 1 km^3, accounting for 69.45% of the total capacity (see Fig. S2 online). On a global scale, Asia has the world's largest number of new reservoirs (4,092) and the highest storage capacity increase (831.15 km^3, 64.55%), followed by Africa. Global patterns by country show that new reservoirs are mainly located in China (1,567), India (960), and Brazil (612) (Fig. 1b). In contrast, the number of new reservoirs in Africa is relatively small, with more than half of the countries having a count lower than 10. China, Brazil, and Ethiopia are the top three countries with the largest reservoir storage capacity, accounting for 30.57%, 11.28%, and 7.18% of the global storage capacity, respectively (Fig. 1c, d).

Information on reservoir storage capacity at the basin scale is essential for managing local water resources and assessing changes in the hydrological cycle (Fig. 1e). The Yangtze River basin has the highest new reservoir storage capacity (171.44 km^3) and the most intensive dam construction (e.g., Three Gorges Dam), followed by the Nile River basin (110.05 km^3). Most (10) of the top 15 basins in terms of total reservoir storage capacity are clustered in South and Southeast Asia (e.g., the Indus River and Yangtze River basins) due to high population densities in these regions and, thus, greater water and energy demands. In contrast, basins in North America rank behind those of other continents overall in terms of either new reservoir number or storage capacity.

Major hotspots of new reservoir construction are observed in the Nile River basin (including Sudan, Egypt, and Ethiopia) (Fig. 1a1), northern India (Fig. 1a2), southern China (e.g., the Yangtze River basin and the Pearl River basin) (Fig. 1a3), and Brazil (Fig. 1a4). Brazil dominated the abundance of post-2000 reservoirs in South America, accounting for 55.30% of the reservoir count and 80.12% of the storage capacity in the continent. The dam construction boom could be associated with the increasing agricultural and heavy industrial interests in Brazil [14]. While the main motivation for building more dams in the Nile River basin of Africa is to meet the hydropower demand with rapidly increasing electrification rates in recent decades [15]. For example, the Grand Ethiopian Renaissance Dam (GERD) in the Nile River basin, with its electricity production, alleviates Ethiopia's severe energy shortages and fully supports rural and urban development throughout the country. This trend will likely continue as the population grows and economies develop in Africa. A similar situation occurred in India (especially the northern part), which is facing a severe shortage of rural electricity, as well as a severe shortage of water for agriculture and household use. Hence, new reservoirs have been built to alleviate the water and electricity shortage. In addition, most of the newly-constructed large reservoirs are concentrated in the upper Yangtze River and the Pearl River, which are featured by large ele-

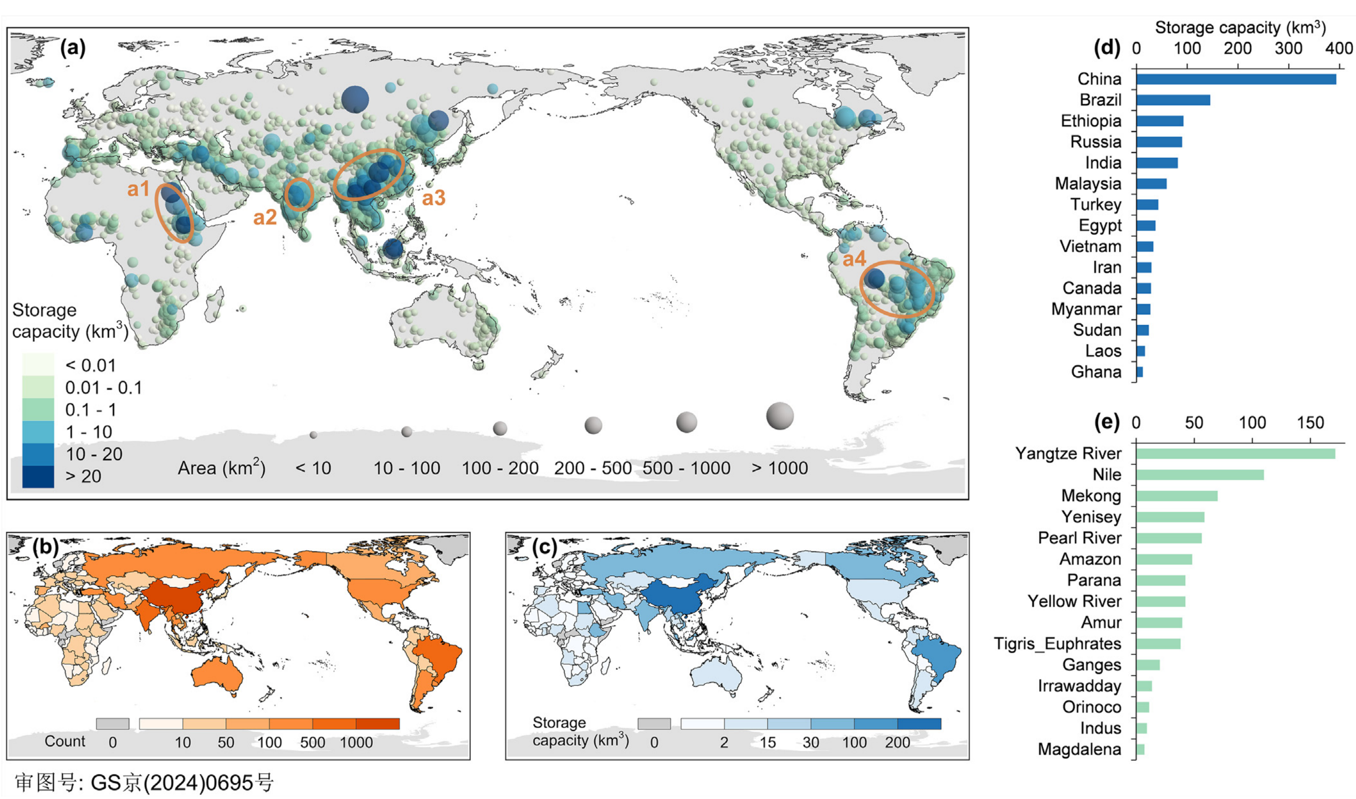


Fig. 1. Post-2000 reservoirs identified in this study. (a) Global distribution and regional hotspots of post-2000 reservoirs. (b, c) Count and total storage capacity of post-2000 reservoirs by country. (d) Top-15 countries with the largest total storage capacities of post-2000 reservoirs. (e) Top-15 mega river basins with the largest total storage capacities of post-2000 reservoirs. Mega basin boundaries are based on Wu et al. [5].

vation drops and greater stream powers [6]. This could be attributed to the water development policies in China, as exemplified by the construction of the Three Gorges Reservoir.

To highlight the improvement in inventorying new reservoirs, we compare GREI-p2k with GeoDAR v1.1, which harmonized GRanD v1.3 and large dams that were geocoded using the ICOLD register. GeoDAR contains 21,515 reservoir polygons, among which 1,193 (of which 920 are larger than 0.5 km^2) were documented to be constructed around the year 2000 or after. GREI-p2k adds another 5,726 post-2000 reservoirs, improving the abundance of post-2000 reservoirs in GeoDAR by nearly four times (Fig. 2a). These additional reservoirs have a total water area of 22,378.93 km^2 and a storage capacity of 455.28 km^3, complementing the post-2000 reservoirs in GeoDAR by 82.18% and 48.29%, respectively. Nearly 50% of the added reservoirs are clustered in China (23.74%), India (14.65%), and Brazil (8.21%) (Fig. 2b), echoing the global pattern previously described and the value of our new data in documenting recently emerged reservoirs in hotspot regions. The histograms in Fig. 2c and d show a significant improvement of GREI-p2k over GeoDAR in representing both surface area and storage capacity of post-2000 reservoirs, especially for medium (with storage capacities between 0.01–0.10 km^3) and small-sized reservoirs (with storage capacities less than 0.01 km^3). GeoDAR also contains 227 additional post-2000 dams without reservoir polygons, and 66 of them have been mapped with reservoir extents in this new post-2000 dataset. Among the 1,030 or so post-2000 reservoirs inventoried in both datasets, the total area in GREI-p2k is 30,804.99 km^2, exceeding that in GeoDAR by 21%. The larger water area in the former is attributable to the usage of maximum water extent observed from 1984 to 2020 as the reservoir polygons. This in theory supplements GeoDAR with a more complete reservoir mask.

To further demonstrate the completeness of GREI-p2k, we conduct a detailed comparison with the GRanD and GDAT global reservoir datasets. GREI-p2k surpasses the existing global reservoir datasets in terms of the count, area, and storage capacity of reservoirs recorded around the year 2000 (Table S1 online). Specifically, GREI-p2k records almost 13 times greater than GRanD and 15 times greater than GDAT. GREI-p2k also outperforms GRanD and GDAT by 132 % and 154 % in terms of reservoir area, respectively. A significant consistency in both area and storage capacity is observed in the reservoirs overlapping with these datasets in GREI-p2k, with correlation coefficients (R^2) exceeding 0.85 (Fig. S3 online). This is especially notable in the near-unity storage capacity ratios, validating the reliability and accuracy of GREI-p2k.

In the era of continued dam boom, the conservation of freshwater ecosystems and natural communities remains a challenge, and research on the ecological and human-social impacts of new reservoirs has so far been limited by insufficient data representation. The GREI-p2k will help to more comprehensively monitor changes in the water budgets of reservoirs globally for more effective water and energy management strategies, as well as to more systematically assess the impact of dams and reservoirs on the global carbon cycle.

Conflict of interest

The authors declare that they have no conflict of interest.

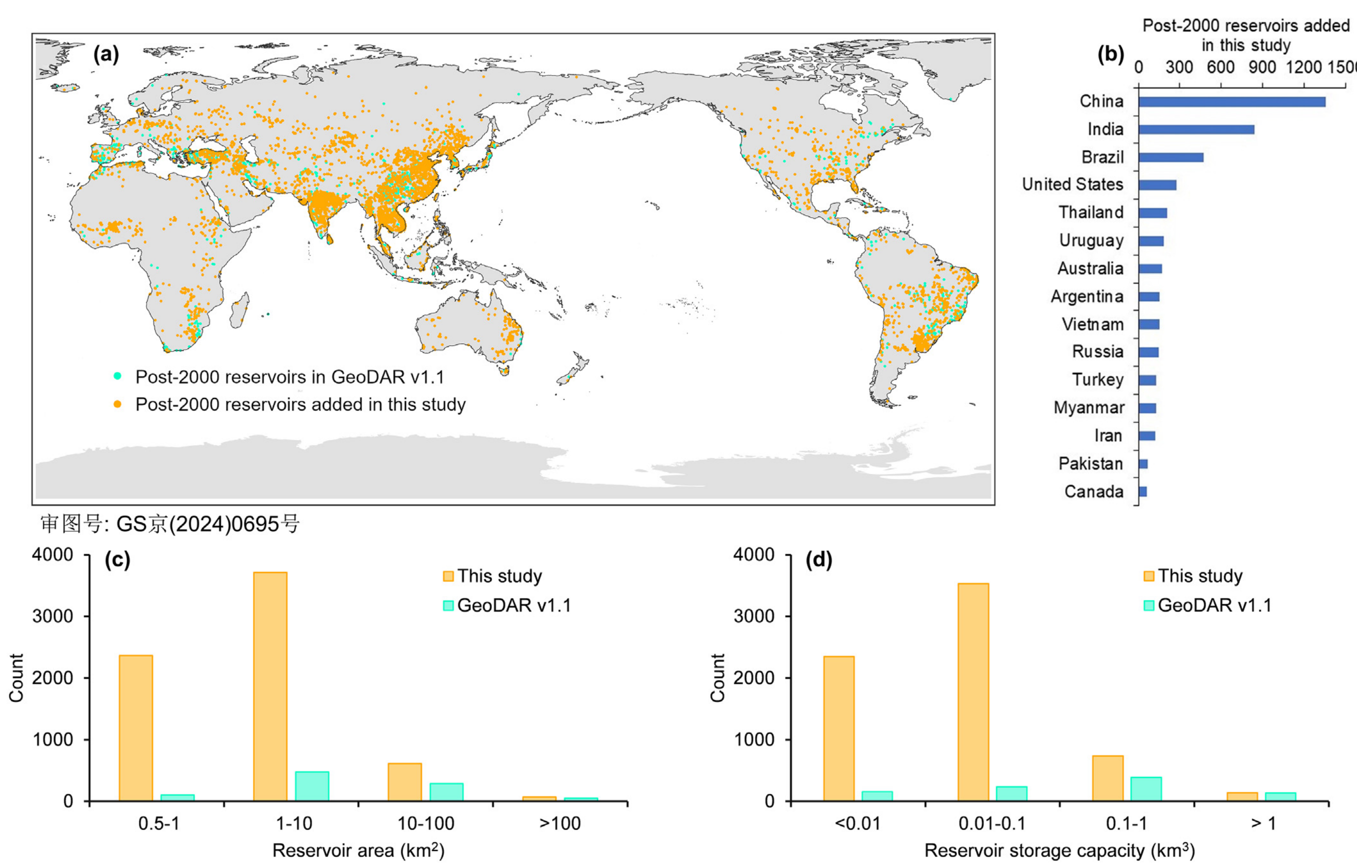


Fig. 2. Comparison of post-2000 reservoirs between GeoDAR (v1.1) and this study. (a) Global distribution of post-2000 reservoirs in both datasets. (b) Top-15 countries with the largest improvements in post-2000 reservoir counts by this study. (c, d) Count distribution by area and storage capacity in both datasets. To make the two datasets comparable, reservoir area and storage capacity statistics for GeoDAR were based on retrieved polygons with an area greater than 0.5 km^2.

Acknowledgments

This work was supported by the National Key Research and Development Program of China (2022YFF0711603), the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA23100102, XDA19090120), the National Natural Science Foundation of China (42371399, 42301431), and the Science and Technology Planning Project of NIGLAS (2022NIGLAS-CJH04, 2022NIGLAS-TJ18). Contributions of Jida Wang and Md Safat Sikder are supported by the NASA Surface Water and Ocean Topography (SWOT) Science Team (80NSSC20K1143). Contributions of Jean-François Crétaux is supported by the CNES TOSCA program of research for his role as PI of the Surface Water and Ocean Topography (SWOT) mission.

Author contributions

Chunqiao Song and Chenyu Fan designed the study. Chenyu Fan, Chunqiao Song, and Jida Wang performed data processing and research analyses on the spatial abundance and hotspot distribution of new reservoirs, with the help of Yaling Lin and Chunyu Yuan, in cataloguing the global reservoir inventory of the post-2000 impoundment (hereafter "GREI-p2k"). Chunqiao Song, Chenyu Fan, Jida Wang, and Md Safat Sikder analyzed the completeness and improvement of GREI-p2k. Jida Wang, Yongwei Sheng, Md Safat Sikder, Jean-François Crétaux, Kai Liu, Tan Chen, Fanxuan Zeng, and Linghong Ke provided insightful feedback on results and discussion interpretation. Chenyu Fan and Chunqiao Song wrote the initial manuscript drafts, with substantial contributions from all authors.

Appendix A. Supplementary materials

Supplementary materials to this short communication can be found online at https://doi.org/10.1016/j.scib.2024.04.043.

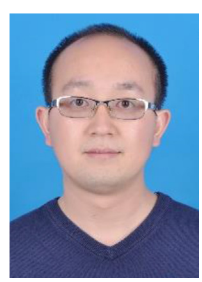
Data availability

The global reservoir inventory of the post-2000 impoundment (GREI-p2k) is publicly available for download from Science Data Bank at https://doi.org/10.57760/sciencedb.15520. The database is supplied in both shapefile and comma-separated values (csv) formats.

References

[1] Chao BF, Wu Y-H, Li Y. Impact of artificial reservoir water impoundment on global sea level. Science 2008;320:212–4.
[2] Wada Y, Reager JT, Chao BF, et al. Recent changes in land water storage and its contribution to sea level variations. Surv Geophys 2017;38:131–52.
[3] Maavara T, Chen Q, Van Meter K, et al. River dam impacts on biogeochemical cycling. Nat Rev Earth Environ 2020;1:103–16.
[4] Winemiller KO, McIntyre PB, Castello L, et al. Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. Science 2016;351:128–9.
[5] Wu Q, Ke L, Wang J, et al. Satellites reveal hotspots of global river extent change. Nat Commun 2023;14:1587.
[6] Song C, Fan C, Zhu J, et al. A comprehensive geospatial database of nearly 100 000 reservoirs in China. Earth Syst Sci Data 2022;14:4017–34.
[7] Li Y, Zhao G, Allen GH, et al. Diminishing storage returns of reservoir construction. Nat Commun 2023;14:3203.
[8] Lehner B, Liermann CR, Revenga C, et al. High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. Front Ecol Environ 2011;9:494–502.
[9] Wang J, Walter BA, Yao F, et al. GeoDAR: Georeferenced global dam and reservoir dataset for bridging attributes and geolocations. Earth Syst Sci Data 2021;2021:1–52.
[10] Zhang AT, Gu VX. Global dam tracker: A database of more than 35,000 dams with location, catchment, and attribute information. Sci Data 2023;10:111.
[11] Pekel J-F, Cottam A, Gorelick N, et al. High-resolution mapping of global surface water and its long-term changes. Nature 2016;540:418–22.
[12] Pickens AH, Hansen MC, Hancher M, et al. Mapping and sampling to characterize global inland water dynamics from 1999 to 2018 with full landsat time-series. Remote Sens Environ 2020;243:111792.
[13] Crippen R, Buckley S, Agram P, et al. NASADEM Global Elevation Model: Methods and progress. Int Arch Photogramm Remote Sens Spatial Inf Sci 2016;41:125–8.
[14] Fearnside PM. How a dam building boom is transforming the Brazilian Amazon. Yale E360 2017;360:26.
[15] Piesse M. Dams in Africa: Balancing food, water and energy security. Australia's independent Future Directions. International (FDI) 2018;2.

Chenyu Fan is a Ph.D. candidate at the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences. Her research topic is remote sensing in lake and reservoir hydrology and global change.



Chunqiao Song is a professor at the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences. His research includes remote sensing in lake-watershed hydrology, remote sensing in resources and environment, surface water resources and global change, and the Tibetan Plateau and the impacts of climate change.