

Key Points

- Here we estimate the inflows and outflows of more than 5,000 global lakes using SWOT observations and the LakeFlow algorithm.
- We find that managed lake outflows are significantly more variable than natural lake outflows in terms of discharge, water surface elevation (WSE), slope, and cross-sectional area change ($p < 0.001$).
- Additionally, same-day inflow and outflow is well correlated in natural lakes but in most managed lakes, correlation is highest when the outflow is lagged.

Motivation

River and lake hydrologies are inherently intertwined but many large-scale hydrologic studies assume that the dynamics of managed lakes are similar to that of natural lakes. This assumption introduces uncertainty, leads to poor discharge estimates downstream of managed lakes, and drastically underestimates human's effect on river discharge and the broader hydrologic cycle. Here we demonstrate that SWOT observations and the LakeFlow algorithm can characterize lake and river dynamics worldwide.

Methods

- We applied the LakeFlow algorithm (Riggs et al., 2023) to all SWOT-observable systems with adequate Version C data availability.
- We used the SWOT Harmonized Prior river-lake database (SWOT-HarP v1.1) (Sikder et al., 2024) to filter our analysis to SWOT observable lakes (Wang et al., 2025) with SWOT observable inflow and outflow reaches (Altenau et al., 2021). We further limited our analysis by filtering the data to ensure that we use high quality SWOT observations.
- We allowed the assignment of a lake inflow or outflow reach to migrate up or downstream by one SWOT reach if the original reach lacks high quality SWOT data.

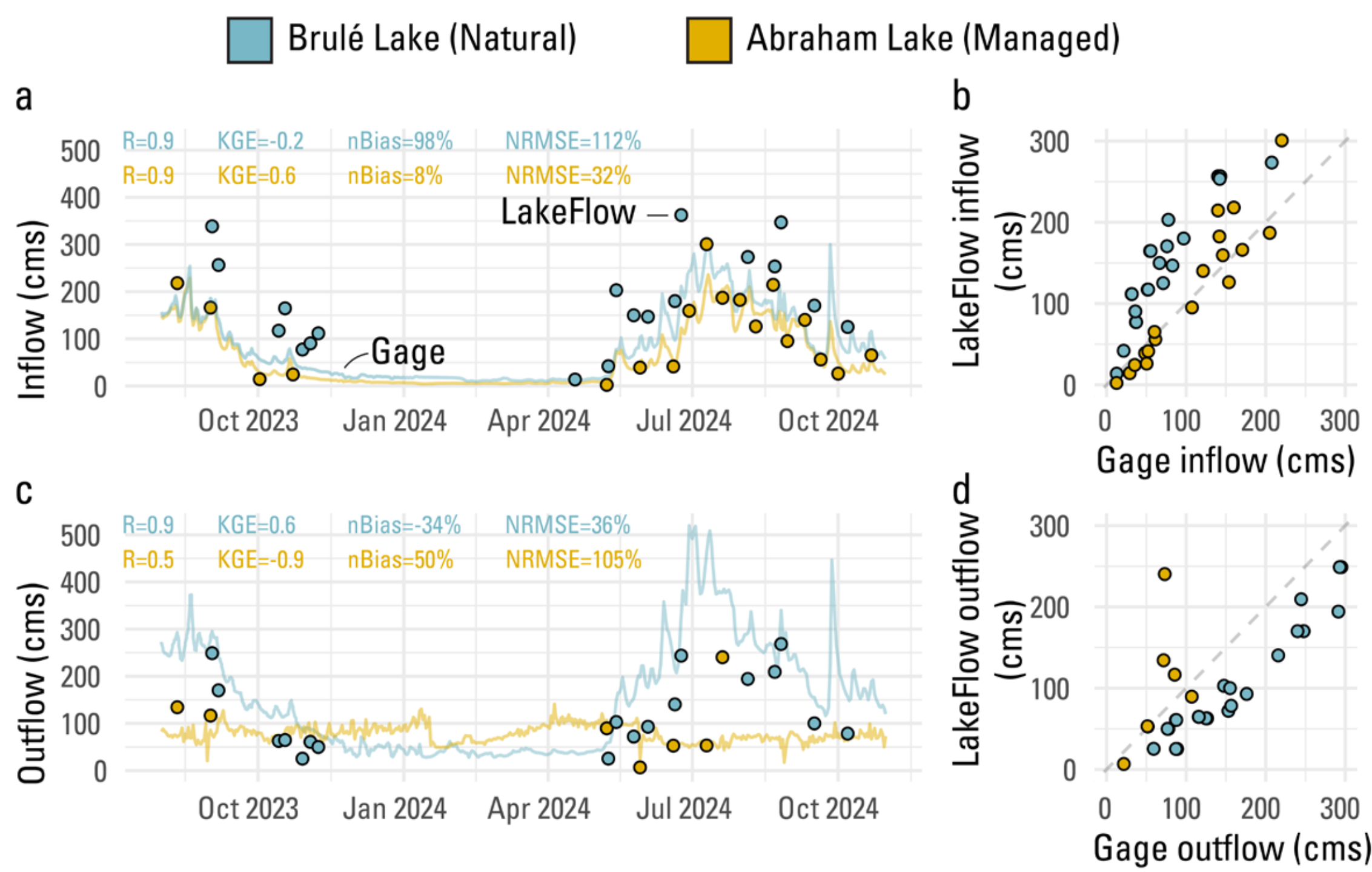


Figure 1. Comparison of LakeFlow inflows and outflows between a natural lake (Brulé Lake) and a managed lake (Abraham Lake), showing differences in the timing and amount of outflow, likely related to management operations.

LakeFlow

$$\text{Lake storage change} = \text{inflow} - \text{outflow}$$

$$\Delta V = n_i^{-1} (A_{oi} + \delta A_i)^{3/2} W_i^{3/2} S_i^{1/2} - n_o^{-1} (A_{oo} + \delta A_o)^{3/2} W_o^{3/2} S_o^{1/2} + Q_i - E$$

- SWOT observables:**
 ΔV = Lake storage change
 W = River width
 S = Slope
 δA = Change in cross-sectional area
- Non-SWOT observables:**
 n = Roughness coefficient
 A_0 = Cross-sectional area at baseflow
 Q_i = Tributary inflow
 E = Evaporation

Apply a Bayesian optimization algorithm to solve for unobserved flow-law parameters (FLP) n and A_0 .

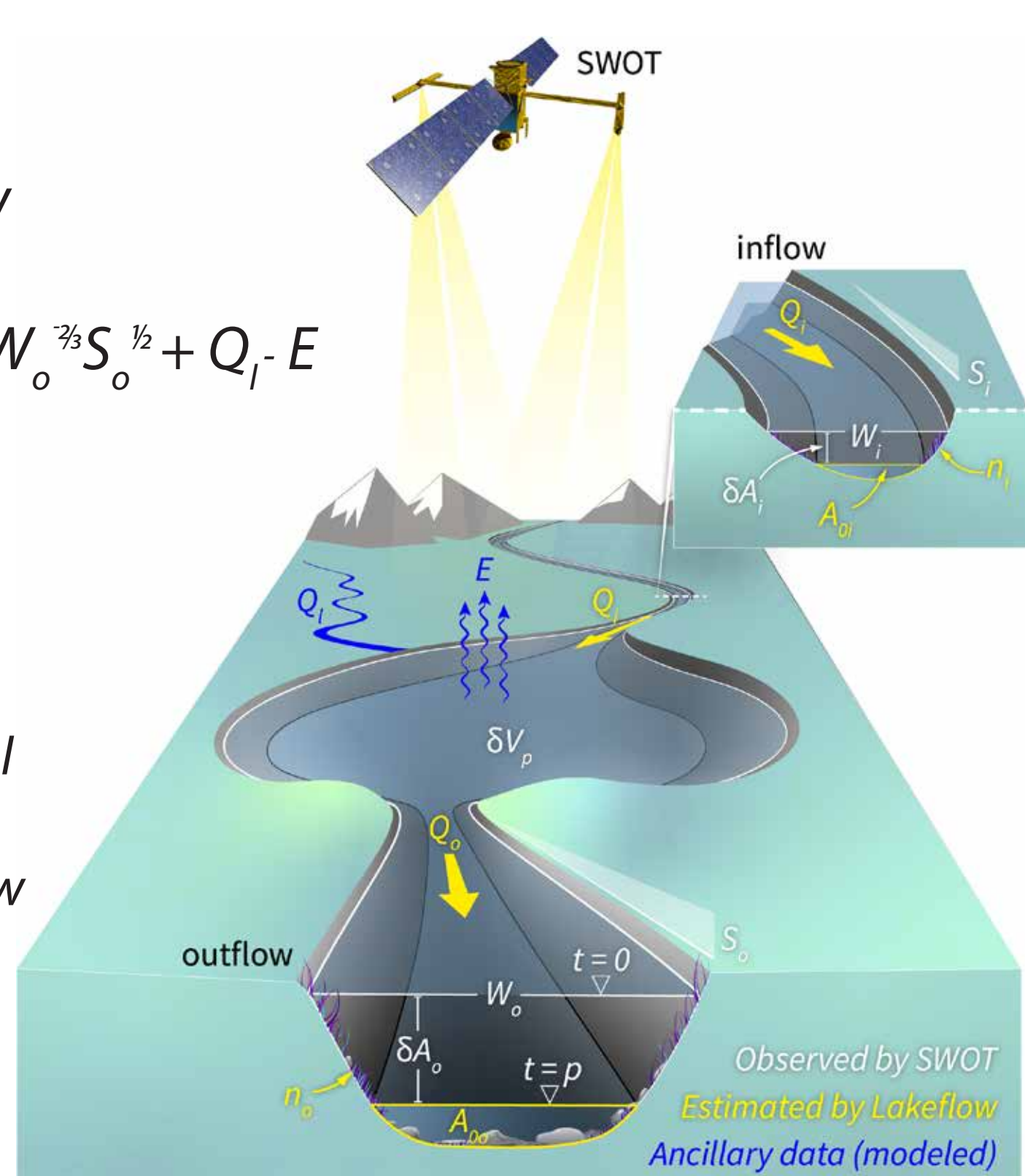


Figure 2. Conceptual diagram of the LakeFlow algorithm which uses repeat SWOT observations of lakes and rivers to estimate the inflows and outflows of lakes. Shown are two snapshots of a lake system corresponding to two SWOT overpasses ($t=0$ and $t=p$). Time p corresponds to the minimum observed flow on record and SWOT observable variables are only shown for $t=p$.

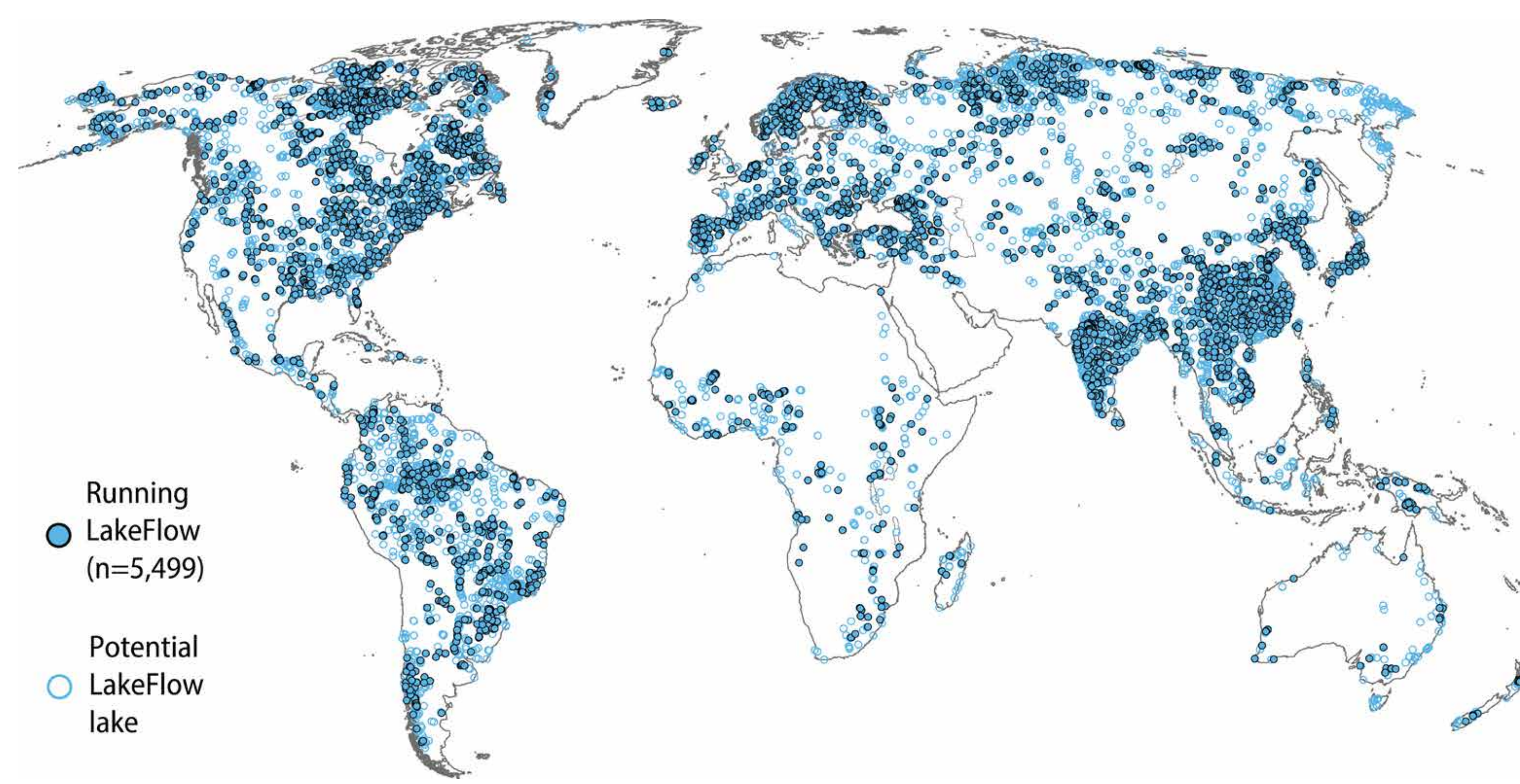


Figure 3. Global distribution of lakes running the LakeFlow algorithm (dynamics at 5,499 lakes, 5,742 inflows, and 5,517 outflows).

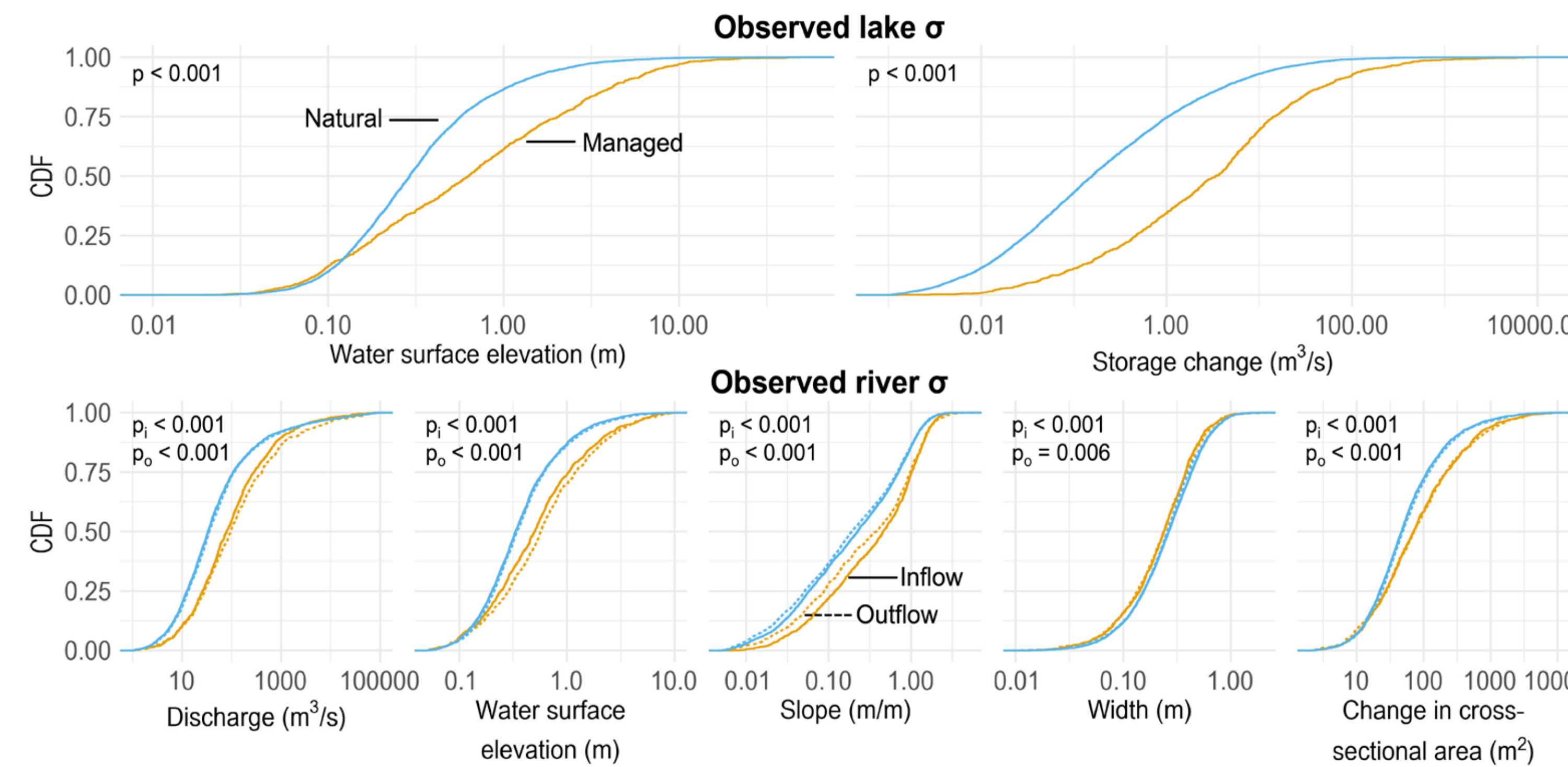


Figure 5. Variability (standard deviation) shown as cumulative distribution functions of SWOT lake (top row) and river observations (bottom row) in natural (blue) and managed (yellow) lake systems, including inflow (solid lines) and outflow (dashed lines) river reaches. Significance values are based on a two-sample, one-sided Kolmogorov-Smirnov test to assess if managed lakes or their river systems are more variable than natural lake systems, with i and o subscripts representing significance values for inflows and outflows, respectively.

Results

- Using SWOT observations, we calculated lake and river dynamics at 5,499 lakes globally (Figure 3).
- We validated lake inflows and outflows using all available river gauges across Canada and the United Kingdom (Figure 4).
- We assessed lake inflow, outflow, and storage dynamics of 922 managed lakes and 4,577 natural lakes globally (Figure 5). We found that managed lakes have significantly ($p < 0.001$) more variability than natural lakes in almost all observed and derived parameters.
- In an analysis over North America, we found that managed lake inflow-outflow lag times are much longer than natural lake inflow-outflow lag times (Figure 6).
- LakeFlow code is now optimized for HPC and cloud computing. LakeFlow has been integrated into the SWOT mission Confluence discharge platform (Durand et al., 2023).

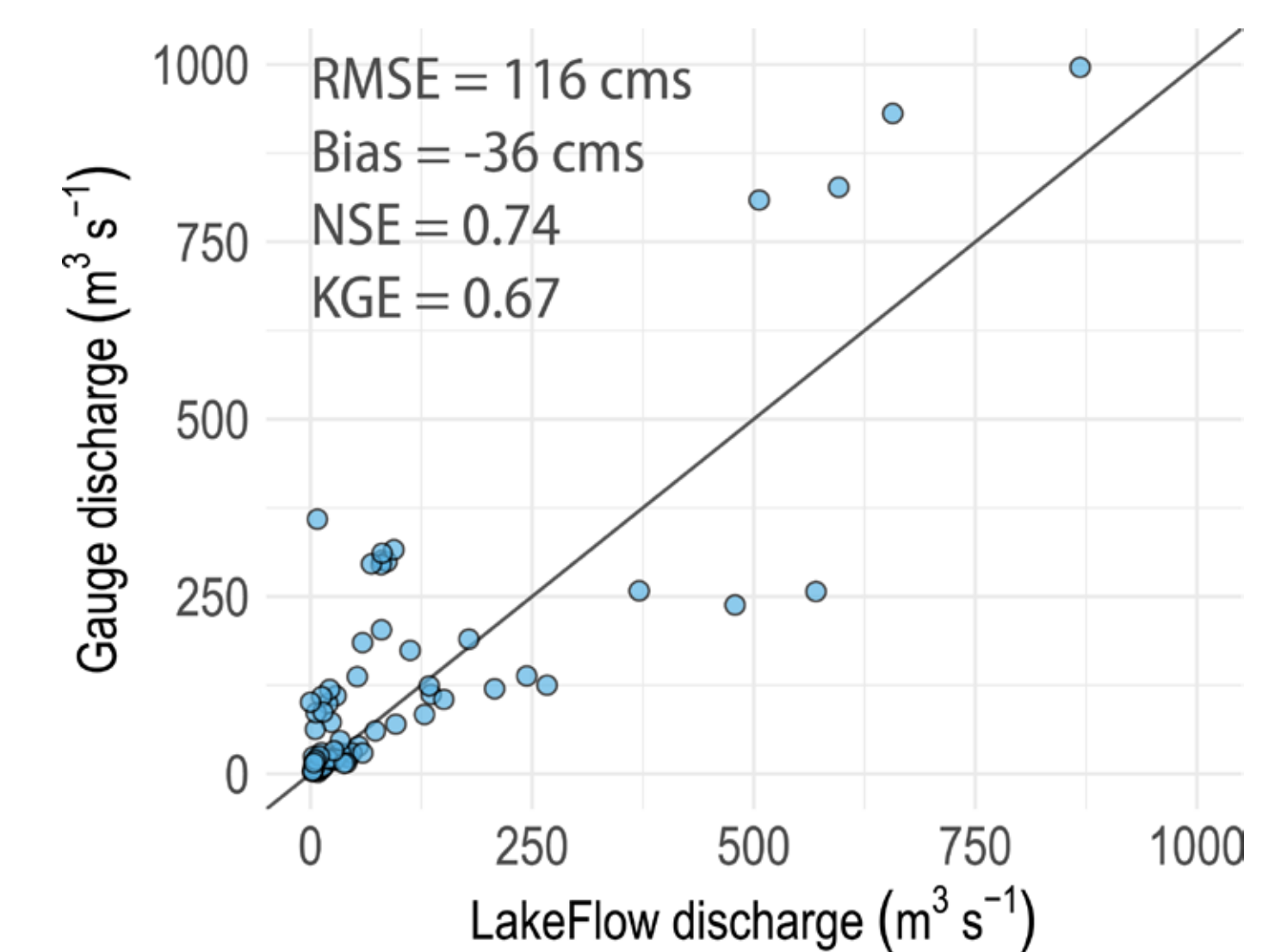


Figure 4. Validation of LakeFlow lake inflow and outflow discharge estimates in Canada and the UK (N=75).

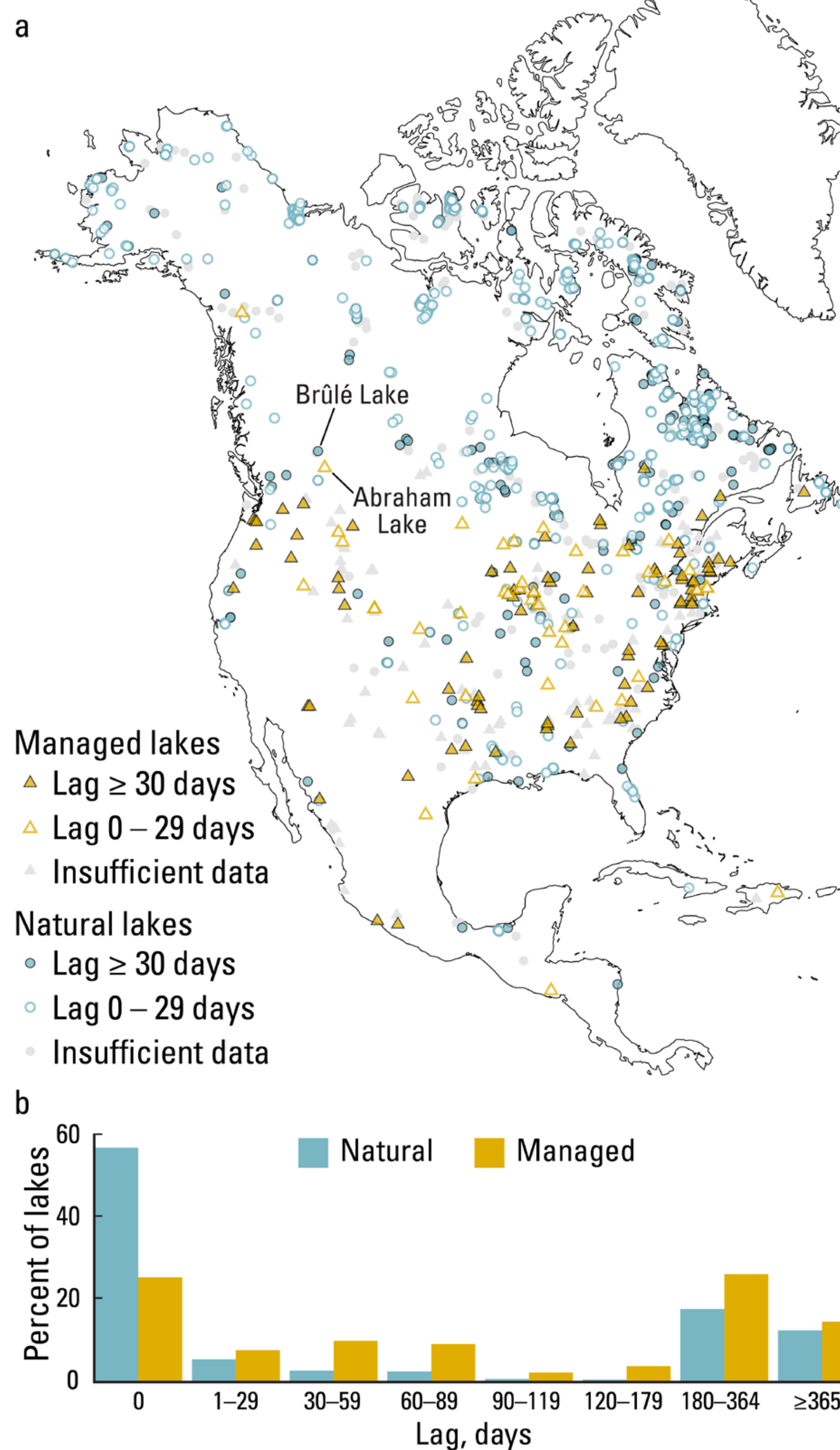


Figure 6. Lag cross correlation results for inflow-outflow discharge estimates at 779 lakes in North America (from Riggs et al., in revision). (a) Map showing each lake's lag time in days at the highest Spearman correlation. (b) The percentage of natural and managed lakes based on the lag time with the highest correlation.

Discussion

- While previous studies have shown that managed lakes are more variable (Cooley et al., 2021), this is the first study to show that these differences extend to lake inflows and outflows.
- Our results indicate that managed lake systems are significantly more variable than natural lake systems in nearly every SWOT observed and derived parameter.
- Future work includes validating LakeFlow globally and inclusion of more accurate ancillary data (e.g. evaporation, tributary inflow).
- Inclusion of LakeFlow's inflow/outflows should be used to account for lake storage impacts on streamflow estimates.

Acknowledgements

This work was supported by the NASA SWOT Science Team (NNH23ZDA001N-SWOTST) with partial support provided by the U.S. Geological Survey Water Availability & Use Science Program and the Virginia Tech Remote Sensing Interdisciplinary Graduate Education Program.

References

Altenau, E. H., Pavelsky, T. M., Durand, M. T., Yang, X., Frasson, R. P. de M., & Bendezu, L. (2021). The Surface Water and Ocean Topography (SWOT) Mission River Database (SWORD): A Global River Network for Satellite Data Products. *Water Resources Research*, 57(7), e2021WR030054. <https://doi.org/10.1029/2021WR030054>

Cooley, S. W., Ryan, J. C., & Smith, L. C. (2021). Human alteration of global surface water storage variability. *Nature*, 591(7848), 78–81. <https://doi.org/10.1038/s41586-021-03262-3>

Durand, M., Gleason, C. J., Pavelsky, T. M., Frasson, R. P. de M., Turmon, M. J., David, C. H., et al. (2023). A framework for estimating global river discharge from the Surface Water and Ocean Topography satellite mission. <https://doi.org/10.1002/essoar.10508946.1>

Riggs, R. M., Allen, G. H., Brinkerhoff, C. B., Sikder, M. S., & Wang, J. (2023). Turning Lakes Into River Gauges Using the LakeFlow Algorithm. *Geophysical Research Letters*, 50(10), e2023GL103924. <https://doi.org/10.1029/2023GL103924>

Riggs, R. M., Dickinson, J. E., Brinkerhoff, C. B., Sikder, M. S., Wang, J., Gao, H., Allen, G. H., (in revision). A step toward inferring management operations with the SWOT satellite by comparing natural and managed lake dynamics. *Geophysical Research Letters*.

Sikder, M. S., Wang, J., Allen, G. H., Sheng, Y., Yamazaki, D., Crétaux, J.-F., & Pavelsky, T. M. (2024). HarP: Harmonized Prior river-lake database (SWOT-HarP v1.1) [Data set]. Zenodo. <https://doi.org/10.5281/zenodo.14205131>

Wang, J., Pottier, C., Cazals, C., Battude, M., Sheng, Y., Song, C., et al. (2025). The Surface Water and Ocean Topography Mission (SWOT) Prior Lake Database (PLD): Lake Mask and Operational Auxiliaries. *Water Resources Research*, 61(3), e2023WR036896. <https://doi.org/10.1029/2023WR036896>