Integrating reservoirs into SWOT's global surface water storage and discharge monitoring

PI: *Jida Wang, Department of Geography and Geospatial Sciences, Kansas State University*
Co-I: *Yongwei Sheng, Department of Geography, University of California, Los Angeles (UCLA)*
Co-I: *George Allen, Department of Geography, Texas A&M University*
Collaborator: *Jean-François Crétaux, Laboratoire d'Études en Géophysique et Océanographie Spatiales (LEGOS), Centre National d'Études Spatiales (CNES), France*

Introduction and Objectives

Water storage in lakes and discharge in rivers are two fundamental components of surface hydrology and understanding their spatiotemporal dynamics is among SWOT's primary science goals. Accordingly, efforts from the previous Science Team for Hydrology have diverged generally in these two directions. The function of reservoirs is akin to both lakes and rivers. Similar to lakes, reservoirs are open water stores, with budgets varying with the residual of local meteorology and surface/subsurface flows. On the other hand, reservoirs are artificially regulated river channels. Tracking reservoir budget variations, therefore, not only improves our understanding of human impacts on surface water storage, but also bridges this understanding to an improved monitoring of river discharge. Given the unique role of reservoirs in bridging storage and discharge, this project is dedicated to an integration of global reservoirs into SWOT's data preparations, algorithm improvements, and scientific understandings of water storage-discharge interactions.

This project will achieve four major objectives (Figure 1). In brief, we will concentrate on a priori data preparation and harmonization (Objectives 1 and 2) before the launch of SWOT, and transition to algorithmic improvement and scientific applications (Objectives 3 and 4) after the launch. These objectives are:

Pre-launch phase (2020 and 2021)
1. Establish an a priori global reservoir database
2. Harmonize a priori reservoir, lake, and river databases.

Post-launch phase (2022 to 2024)
3. Improve discharge estimations at store-river connections
4. Understand reservoir impacts on seasonal storage-discharge interactions.

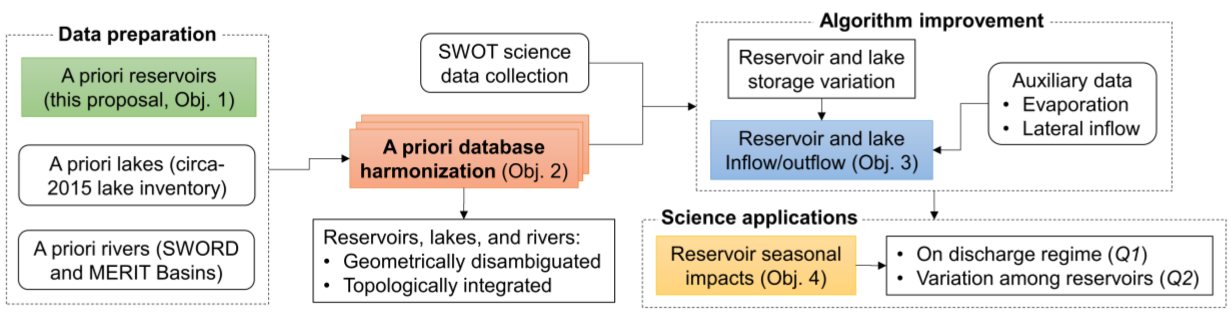

Figure 1. Research objectives. Rectangles indicate results expected from this proposal.

Approach

1. Establishing an a priori global reservoir database for SWOT

We will synergize our own research accumulation in dam and reservoir inventory with other available registries and inventories, to compile a comprehensive a priori global reservoir database for SWOT. This a priori database will include 1) fine-detailed spatial masks of artificial reservoirs, and 2) their attributes and metadata (e.g., inundation probability, water height reference, and visibility to SWOT) that are critical to suffice SWOT's accuracy and consistency requirements for reservoir storage monitoring.

Dam/reservoir locations will be collated from regional dam registries, reservoir and river barrier inventories (e.g., the Global Reservoir and Dam Database (GRanD) (Lehner et al. 2011), the GlObal geOreferenced Database of Dams (GOODD) (Mulligan et al. 2020), and the Global River Obstruction Database (GROD) (Yang et al. 2019)), and our georeferenced World Register of Dams of the International Commission on Large Dams (GeoICOLD, https://lakewatch.users.earthengine.app/view/geoicold; Figure 2). Dam locations will then be combined with long-term water dynamics mapped from spectral imagery and high-accuracy DEM to retrieve reservoir inundation probability and maximum extents. The susceptibility of reservoirs to SWOT's topographic layover will be evaluated using the simulator developed from our previous Science Team effort (Sheng et al. 2017). Reservoir reference water heights (e.g., minimum and maximum levels), which are crucial information for SWOT phase unwrapping, will be acquired from the constellation of satellite altimeters in coordination with LEGOS/CNES. We will prioritize the reservoirs larger than SWOT's observation requirement (250 m by 250 m), but will not purposely exclude smaller reservoirs as they are valuable for improving discharge simulation via hydrological models. This dataset will complement the river and lake algorithms and data products that are currently being developed by the Science Team.

2. Harmonizing a priori reservoir, lake, and river databases

The developed a priori reservoirs will be integrated to our UCLA Circa-2015 Lake Inventory (Sheng et al. 2016), which will form an a priori global water store dataset where reservoirs are distinguished from natural lakes (see preliminary result in Figure 2). The integrated lake-reservoir dataset will then be carefully harmonized with existing a priori river databases. We will mainly use two latest and complementary river databases: 1) the SWOT a priori River Database (SWORD) (Altenau and Pavelsky 2019), which is an enhanced version of the Global River Widths from Landsat (GRWL) database (Allen and Pavelsky 2018) with improved drainage connectivity for river reaches >30 m, and 2) MERIT Basins (Lin et al. 2019), which contains more detailed river flowlines and their unit catchments channelized from the 90-m-resolution MERIT Hydro hydrography dataset (Yamazaki et al. 2019). Through this harmonization, each hydrologic unit, i.e., lake, reservoir, and free-flowing river reach, will be geometrically disambiguated so as to ensure the accuracy of SWOT's storage change and discharge estimations, and meanwhile topologically connected to enable the understanding of storage-discharge interactions. Special emphasis will be placed on the connections between rivers and water stores (lakes and reservoirs) since this complex interface is critical for improving discharge estimations, and has not been fully exploited in the existing algorithms.

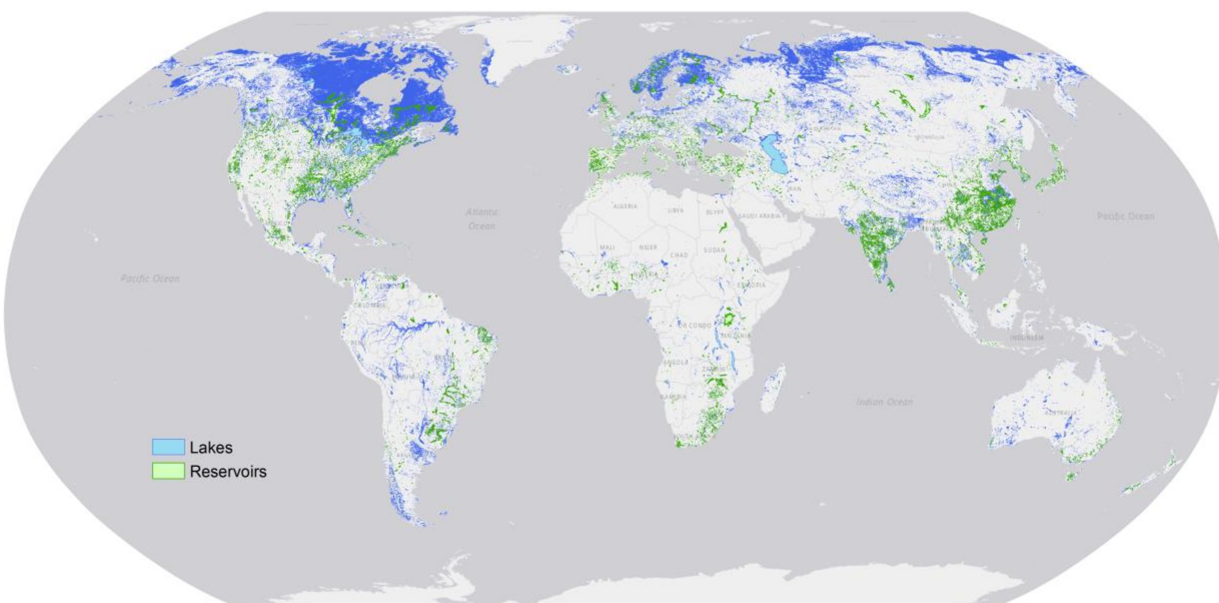

Figure 2. Preparation for the a priori lake-reservoir database for SWOT. Shown in this global map are about 9 million lakes larger than 0.4 ha in the UCLA Circa-2015 Lake Inventory, intersected or superimposed by over 40,000 reservoirs (preliminary estimate) jointly from GeoICOLD, GOODD, and GRanD.

3. Improving discharge estimations at store-river connections

Using SWOT's data measurements, we will evaluate a method that aims to improve the estimates of discharge at reservoir-river connections (i.e., reservoir inflow and outflow), through a modification of the MetroMan algorithm (Durand et al. 2014) to account for the mass conservation between reservoirs and rivers. We will start the algorithm development with reservoirs, but aim to also include lake-river connections that are visible to SWOT.

The concept bridges together reservoir storage changes (ΔV), which are relatively easy for SWOT to measure, to an improved parameterization of the inflow and outflow channel properties that are not directly observable to SWOT but are necessary for discharge estimations. We focus on the inflow and outflow reaches in close vicinity of the reservoir, because their discharge difference (ΔQ) is typically the first-order control on ΔV and the channel parameterization will thus largely rely on SWOT-observed ΔV. Technically, we will adopt the Manning's equation, where surface water width, longitudinal gradient, and the change in cross-section area are directly measurable by SWOT, whereas channel friction coefficient and baseflow cross-section area are not observable but often time invariant. Values of the two unobservable properties for both inflow and outflow reaches will be solved by constraining ΔQ, which varies as a result of repetitive measurements of the observable reach variables, to measured ΔV. To further constrain the uncertainty, we will integrate multi-source datasets and model simulations to take into account other important controls, such as reservoir surface evaporation and reservoir lateral inflow from tributaries too small to be observable by SWOT. The parameterized channel properties will then enable the calculations of reservoir inflow and outflow at any time given SWOT's measurement of the observable reach variables.

4. Understanding the roles of reservoirs in seasonal storage-discharge interactions

How reservoirs impact the river regimes has been a long-standing question. Results from the previous objectives, particularly the estimated reservoir inflow/outflow and storage variations during SWOT's initial data collection years, will benefit an improved understanding of reservoir seasonal impacts on the global river discharge. Specifically, we will answer two questions: "How do reservoirs alter the intra-annual flow regime in global rivers (Q1), and how does the impact vary in reservoir purpose, stream order, climate aridity, and geopolitical settings (Q2)?" We hypothesize that global reservoirs significantly counteract the natural intra-annual variability in river discharge, with impacts more amplified in high-order streams, flood-prone regions, (semi)arid climates, and populated watersheds.

We will start with quantifying the fraction of river discharge altered by each reservoir. To assess how the impact propagates downstream, we will integrate the alterations from all reservoirs upstream to each reservoir successively, and calculate the accumulative effects relative to discharge. The calculated time series will then be used to reveal how reservoirs, both individually and collectively, counteract or augment the natural seasonal discharge and alter the overall intra-annual variability. By discretizing these results, we will provide a global classification of river reaches by the level of reservoir impacts, largely based on SWOT observations. Quantified seasonal behaviors of global reservoirs will then be contrasted by their registry purposes (e.g., water supply, flood control, and hydropower), located climate conditions, stream order and width, and geopolitical settings (e.g., whether in transboundary basins). This contrast is critical to parameterizing reservoir operations in hydrological modeling and reconciling water management in climate-sensitive and transboundary watersheds.

Anticipated Results and Milestones

The project outcomes are tailored for some of the most pressing needs for SWOT. The result of Objective 1 will be a comprehensive a priori global reservoir database that is presently missing in the Science Team. Different from some existing reservoir inventories, this proposed reservoir database will include high-accuracy spatial masks for a vast number of reservoirs and also a selection of the most critical a priori attributes and metadata required to maintain SWOT's accuracy requirements.

The result of Objective 2 will be a fully harmonized a priori surface water database, where reservoirs, lakes, and free-flowing river reaches are geometrically disambiguated but topologically integrated. This harmonization will dovetail with, rather than replicate or replace, the ongoing Science Team efforts. Its outcome will be a necessary synergy of major SWOT a priori datasets so that they can complement each other to enable an integrated monitoring of both water storage and discharge. The harmonized a priori store-river databases will be ready before the launch of SWOT.

Results of Objective 3 will include 1) key channel properties (friction coefficient and baseflow cross-section areas) for SWOT-visible inflow/outflow reaches around each reservoir/lake, and 2) discharge estimates and their uncertainties for these reaches. We will also deliver the open-source code for our algorithm that produces the above estimates and allows for continued inflow/outflow estimations using SWOT data beyond the proposal period. These deliverables will complement the existing discharge algorithms which focus on regular river reaches rather than the store-river interface.

Results of Objective 4 will fulfill one of the core scientific values of our produced data and algorithm: improving our understanding of how reservoirs function as a "bridge" between water storage and discharge. We aim to provide a spatially-explicit revelation of 1) the seasonal impacts of reservoir water regulation on the flow regimes along the world's major rivers, and 2) the variation of global reservoir behaviors by the design purpose, and hydroclimate and geopolitical settings. These results have immediate implications for water resource managements and improving reservoir operation schemes in hydrological models.

References

Allen, G.H. and Pavelsky, T.M. (2018) Global extent of rivers and streams. Science 361(6402), 585-587.

Altenau, E. and Pavelsky, T. (2019) SWOT A priori River Database (SWORD) update. SWOT Science Team Meeting, Bordeaux, France, June 17-20, 2019.

Durand, M., Neal, J., Rodriguez, E., Andreadis, K.M., Smith, L.C. and Yoon, Y. (2014) Estimating reach-averaged discharge for the River Severn from measurements of river water surface elevation and slope. Journal of Hydrology 511, 92-104.

Lehner, B., Liermann, C.R., Revenga, C., Vorosmarty, C., Fekete, B., Crouzet, P., Döll, P., Endejan, M., Frenken, K., Magome, J., Nilsson, C., Robertson, J.C., Rodel, R., Sindorf, N. and Wisser, D. (2011) High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. Frontiers in Ecology and the Environment 9(9), 494-502.

Lin, P., Pan, M., Beck, H.E., Yang, Y., Yamazaki, D., Frasson, R., David, C.H., Durand, M., Pavelsky, T.M., Allen, G.H., Gleason, C.J. and Wood, E.F. (2019) Global reconstruction of naturalized river flows at 2.94 million reaches. Water Resources Research, 55, 6499-6516.

Mulligan, M., van Soesbergen, A. and Sáenz, L. (2020) GOODD, a global dataset of more than 38,000 georeferenced dams. Scientific Data, 7, 31.

Sheng, Y., Ke, L., Song, C. and Lettenmaier, D.P. (2017) SWOT global layover modeling and global lake observability from SWOT. SWOT Science Team Meeting and Cal/Val Workshop, Toulouse, France, June 26-29, 2017.

Sheng, Y., Song, C., Wang, J., Lyons, E.A., Knox, B.R., Cox, J.S. and Gao, F. (2016) Representative lake water extent mapping at continental scales using multi-temporal Landsat-8 imagery. Remote Sensing of Environment 185, 129-141.

Yamazaki, D., Ikeshima, D., Sosa, J., Bates, P.D., Allen, G.H. and Pavelsky, T.M. (2019) MERIT Hydro: A high-resolution global hydrography map based on latest topography dataset. Water Resources Research 55(6), 5053-5073.

Yang, X., Belanger, M., Byron, D.K., Dolan, W., Galit, H., Januchowski-Hartley, S., Jorrisen, M., Langhorst, T., Lawton, E., McQuillan, K.A., Pavelsky, T., Pawar, S., Ross, M. and Whittemore, A. (2019) Our fragmented rivers – mapping human-made river obstructions around the globe. American Geophysical Union Fall Meeting, San Francisco, California, December 9–13, 2019.