Title: Gaps Between Western U.S. Reservoir Inflows and Headwater Precipitation Timing, Amount, and Phase

Short Title: Headwater hydrology for reservoir operations
Focal Areas: Large Hydropower
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Summary:

Snowmelt from mountain headwater basins supplies approximately 80% of the runoff to reservoirs in the western United States (WUS), and is therefore a key component of western hydropower. Yet predicting runoff from hydrometeorological data in complex terrain —and its sensitivity to disturbances and extremes—remains highly uncertain. Basic science uncertainties include how inflows to reservoirs respond to shifts in precipitation timing, amount, phase (rain versus snow), the impacts of evolving forest/land cover due to disturbances, and the often overlooked role of groundwater in the mountain hydrologic cycle. Challenges to address these questions arise in validating and downscaling climate data for use in physics-based or AI-driven watershed models, assessing biases and process fidelity in these models, and scaling process understanding from plot/hillslope/intensive field campaigns to watershed and hydropower-relevant scales. Further, water management restrictions and policies drive reservoir operation guidelines such as stationary rule curves, with the potential to inhibit energy production and water supply.

1.Existing Challenges:

1.a The Roles of Mountain Groundwater

Reservoir inflows are declining in many regions even in years with average snowpack and precipitation (Hogan & Lundquist, 2024; Xiao et al., 2018). The disconnect varies in time in ways that are not understood, but may include interactions with declining mountain groundwater. As air temperature increase and low-to-no snow conditions become more prevalent, a series of changes to the mountain water cycle are possible, including increases in evapotranspiration, declines in groundwater recharge, and alterations to surface water-groundwater interactions (Meixner et al., 2015, Siirila-Woodburn et al., 2022). Studies point to the potential for declines in runoff with less snow and more rain (Berghuijs et al., 2014), so that runoff that does occur is increasingly reliant on groundwater (Carroll et al., 2019). Although difficult to observe in complex mountain terrain, recent studies point to the prevalence of old water buffering streamflow (Meyers et al., 2021, Thiros et al., 2024, Carroll et al., 2024). Reconciling runoff observations with geochemical tracers of hillslope runoff processes, groundwater data, and advanced subsurface modeling is required to quantify the contribution of groundwater to reservoir inflows, and the impacts to reservoir operations as groundwater depletion occurs.

1.b Hydrometeorological Data Downscaling in Complex Terrain

The current generation of global models and atmospheric reanalyses are too-coarse to capture heterogeneity of snowfall and snowmelt energetics in mountain terrain (Wrzesien et al., 2019). Water resource studies regularly use dynamical downscaling models (Liu et al., 2017; Prein et al., 2015) and high-resolution Numerical Weather Prediction (NWP) models (Benjamin et al., 2016; Powers et al., 2017), though such models can still have significant biases in snowpack relevant fields (Rudisill et al., 2024) that are difficult to quantify given data sparsity in mountain terrain (Lundquist et al., 2019). Relatedly, selecting appropriate downscaling methods, bias-corrections, and appropriate GCM projections for water resource planning is an area of active work (Rahimi et al., 2024).

A substantial fraction of WUS precipitation falls within several degrees of freezing (Bales et al., 2006). Better observations of precipitation phase are needed, as traditional empirical metrics can perform poorly (Jennings et al., 2025). NWP models, while demonstrating skill in some snow climates (Currier et al., 2017), require further validation in hard-to-observe terrain. Further, rain falling onto snowpacks can cause rapid melt and flooding, but the physical mechanisms through which rain-on-snow manifests as extreme runoff is open to investigation (Heggli et al., 2022), and could be valuable improvements for reservoir operations under extremes and new approaches such as forecast informed reservoir operations (FIRO).

Snowpack water storage is the first-order variable for runoff prediction, but estimates of this basic quantity merit additional efforts towards quantification using novel model and data-informed fusion products. Low-to-no-snow conditions not only portend lower runoff volumes (Siirila-Woodburn et al., 2021), but also will limit the efficacy of observational networks for measuring snow (Cowherd et al., 2024). The areal extent of snowpack is well-monitored from space (Notarnicola, 2020), but mass estimates remain elusive. Airplane based LIDAR is the current-gold standard for mapping snow mass, but is limited in spatial and temporal extent. Satellite radar missions (Kellogg et al., 2020) may successfully retrieve snow mass but scientific challenges remain. Recent work suggests targeted placement of observations may provide equivalent utility as basin-wide snowpack mass (Raleigh et al., 2025) for water-yield modeling.

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1.c Landscape Disturbance and Human Management Impacts on Snowpack Processes

The impact of forest disturbance on snow processes and subsequent runoff contradicts simplistic rules-of-thumb, as forest/snow intersections occur through a number of competing mechanisms (Lundquist et al., 2021). There is a need for basic science research to understand how landscape disturbances, including large-scale wildfire, impact snowmelt, accumulation, and the partitioning of water into evapotranspiration, recharge, and runoff. The extent to which human management of forests can optimize snow retention and runoff, with multi-objective benefits to reservoir operations, merits further inquiry, though the solutions are likely climate and ecosystem dependent (Dickerson-Lange et al., 2021).

Quantifying the impact of established or novel weather cloud seeding activities on precipitation and reservoir inflows is an area of ongoing research, including quantifying the frequency and extent of storm systems with conditions favorable for seeding, as well as optimal design for ground based seeding instruments.

2. Near-Term Opportunities:

Current challenges to reservoir inflows have never been greater, highlighting the need for actionable science. Minimum flow forecasts suggest minimum power pool in the Upper Colorado may be achieved by fall of 2026[1], underscoring the vital importance of improving seasonal-to-subseasonal runoff predictions. Reservoir operations at the single storm-scale are trending towards more active management, with the adoption of FIRO policies across the WUS[2] that may increase reservoir storage into the dry season by limiting winter and spring release.

Key science areas that need to be advanced to address the challenges and respond to opportunities are as follows:

2a. Incorporating Basic-Science Knowledge from Intensive Surface-to-Subsurface Study Sites into Physics Based or AI models for Runoff Prediction

Long standing, field based intensive research efforts in water-resource vital mountain terrain have yielded insights into runoff generation processes at the sub-watershed, hillslope, and plot scales. Key insights from observations, as well as the physical processes driving the observations, are needed for achieving a basic level of skill in models so that they can reproduce hydrologic phenomena such as hydrographs. Multi-year observations of high-elevation water cycles, such as those from the Watershed Function Scientific Focus Area (Hubbard et al., 2020), provide these difficult to obtain data and subsequent scientific insights. Examples include the temporal decline in groundwater storage (Tokunaga et al., 2019), groundwater age distributions (Thiros et al., 2023), and the spatio-temporal rain-snow partitioning to plant water use or streamflow (e.g. Sprenger et al., 2022). Importantly, these unique observations provide opportunities for training data with new AI modeling approaches to be applied elsewhere.

2b. Leveraging Insights from Atmospheric Observatories

DOE investments in atmospheric observations in complex terrain, including the Surface Atmosphere Integrated Field Laboratory (SAIL) and STORMVEX ARM field campaigns also provide important benchmark data for AI models to capture essential atmospheric processes that drive surface hydrology. Such laboratories can and have informed challenges such as precipitation phase modeling, cloud-seeding-relevant microphysical processes, snowmelt energy budgets (Rudisill et al., 2025; Sedlar et al., 2024), quantitative precipitation estimates (Heflin et al., 2024), and NWP model competency in complex terrain (Adler et al., 2023; Rudisill et al., 2024). Research is needed on optimal AI methods for utilizing these many, heterogeneous data sources to advance estimates of water inputs to and output from these watersheds, to estimate snowpack extent and water content, and to identify new observational data needs.

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