River Research and Applications

Research Article

A Functional Flows Framework for the Terminal Great Salt Lake Basin: Can we Have our Lake and Drink it Too?

Submission ID b0ce800b-3316-414a-9cae-ff7ac78d5fd1

Submission Version Initial Submission

PDF Generation 15 Dec 2025 18:21:39 EST by Atypon ReX

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A Functional Flows Framework for the Terminal Great Salt Lake Basin: Can we Have our Lake and Drink it Too?

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Abstract

Terminal basins provide unique aquatic environments that are often highly sensitive to streamflow contributions, making them a focal point for environmental water management. However, the environmental water needs for terminal lake, wetland, and river ecosystems, and how they relate, remains a fundamental knowledge gap that constrains our ability to efficiently manage these globally critical and imperilled systems. Recent efforts to increase streamflow to Great Salt Lake (GSL) and reverse lake decline underscore the need to simultaneously consider instream flow requirements for contributing rivers and delivery needs for the GSL peripheral wetlands, so water dedicated and delivered to the GSL can achieve additional ecological benefits to the larger basin as a whole. This paper introduces a functional flows framework for the GSL basin. Functional flows are specific components of the annual hydrograph and interannual variability that are critical to aquatic ecosystem health. We characterize functional flows and associated hydrologic metrics for GSL basin's rivers and wetlands, and calculate functional flow metrics for reference stream gages across the basin. Finally, we discuss how this approach could help address persistent challenges to environmental water management in the GSL basin related to coordination, adaptive management, and resource constraints. Functional flows provide a foundation for consistently and transparently quantifying when, where and how much water is needed to achieve critical environmental functions in upland rivers and wetlands as well as GSL itself.

Introduction

Terminal (endorheic) lakes, their adjacent wetlands, and contributing rivers provide unique and diverse aquatic environments (Cooper & Koch, 1984; Donnelly et al. 2022; Herring et al. 2025; Micklin 2010; Zadereev et al. 2020). Most terminal lakes lie in arid or semiarid regions (Wurtsbaugh et al. 2017; Herring et al. 2025) and are therefore highly sensitive to streamflow contributions. Their aquatic ecosystems are especially vulnerable – but also critical focal points for restoration and efficient environmental water management. Despite decades of research on the environmental flows needed to sustain and restore river ecosystems (Tharme 2003), far less attention has been given to environmental water needs for terminal lakes (Huang et al 2023; Great Salt Lake Strike Team, 2025) and their connected wetlands (Powell et al. 2008; Medwet 2020; Yang et al. 2016). Although river topology suggests that the native species in connected river, wetland, and lake ecosystems should be adapted to similar, if slightly offset, flow magnitude, timing, frequency, duration and rate of change, their water needs and management are typically considered separately. The environmental water needs for terminal lake, wetland and river ecosystems – and how they relate – remains a fundamental knowledge gap that constrains our ability to manage environmental water holistically or efficiently for these globally critical and imperilled ecosystems.

Environmental flows are widely recognized as critical to maintaining and restoring river ecosystems (Poff et al. 2017), and many methods exist to estimate environmental flow needs (Tharme 2003) that can be generally grouped into bottom-up and top-down approaches. Bypass flows are a common bottom-up approach to meet species-specific habitat requirements, but they ignore many other important functions and species, and are often site-specific and resource-intensive to define (Klopries et al. 2018). As restoring the full unimpaired flow regime is generally infeasible, top-down streamflow-based approaches retain or mimic key aspects of the unimpaired flow regime. However, challenges remain related to flow metric selection and redundancy and their biological relevance (e.g., Poff and Zimmerman 2010; Olden and Poff 2003). Furthermore, many other alterations to aquatic ecosystems (including altered water quality, morphology, vegetation, and competition/predation by non-native species) underscore the need to focus on maintaining critical functions rather than simply mimicking the natural hydrograph.

A functional flows approach to guide the selection of flow metrics, as proposed by Yarnell et al. (2020), instead relies on the identification of discrete seasonal aspects of the natural flow regime that have documented or generally recognized relationships with ecological, geomorphic, or biogeochemical processes. In the absence of sufficient resources to develop detailed, site-specific empirical or mechanistic flow-ecology relationships, the functional flows approach assumes that managing for these seasonal flow components, as quantified by a set of flow metrics, can preserve the necessary hydrologic patterns upon which native species depend. Studies have demonstrated the effectiveness of this method (e.g., Baruch et al. 2024; Cuddy et al. 2024). California's functional flows framework and associated technical interagency workgroup (CEFWG, 2021; Stein et al. 2021) has served to address environmental water knowledge gaps and coordination challenges through development of a standardized, flexible process and quantitative tools to characterize key flow-mediated riverine functions, including in highly modified (Taniguchi-Quan et al. 2022) and groundwater-dominated (Yarnell et al. 2022) systems. However, this approach has had limited application outside of California and Australia, and has not been applied to wetland ecosystems.

Rivers, wetlands and lakes are hydrologically and biogeochemically connected through numerous surface and subsurface pathways (Vannote et al. 1980; Leibowitz et al. 2023). In arid terminal basins, largely unidirectional connections make terminal lakes and their peripheral wetlands highly sensitive to changes in streamflow and water quality. However, the hydrologic connectivity of terminal basins, as well as the resulting linkages between water availability, water quality, and aquatic ecosystems, are often poorly understood (Herring et al. 2025). Furthermore, these connections are rarely explicitly accounted for in water management, as underscored by water withdrawals and diversions that exceed lake inflows, which has reduced the area and connectivity of lakes, wetlands (Null and Wurtsbaugh 2020), and riparian areas (Wurtsbaugh et al. 2017; Sterle et al. 2020). Understanding and leveraging these natural and anthropogenically modified hydrologic linkages is crucial to efficiently managing water for humans and ecosystems.

Given the substantial consumptive water uses and persistent drought in the terminal Great Salt Lake (GSL) basin, Utah, U.S., a coordinated water management framework that considers environmental water needs for rivers, wetlands, and GSL would leverage and reinforce recent legislation, water policy, and coordinated management targeted at getting more water to GSL. While recent efforts have characterized environmental water needs for the lake (Great Salt Lake Strike Team, 2025) and lake level effects on lake and wetland ecosystems (Utah Department of Natural Resources, Division of Forestry, Fire and State Lands, 2013), environmental water needs for contributing rivers and GSL peripheral wetlands remain poorly defined. Furthermore, only a small percentage of GSL basin streams have environmental flow protections of any type. These constraints limit the potential for water dedicated to GSL to achieve additional ecosystem benefits as it is shepherded downstream. This paper introduces a functional flows framework for Utah's GSL basin to address outstanding challenges and catalyze interagency and interdisciplinary collaboration related to environmental water management. A functional flows approach to water management in a fully allocated system like the GSL basin offers a pathway for linking current understanding of riverine and wetland ecosystem processes with discrete, quantifiable hydrologic metrics for a broad range of species, including linkages between water quantity, water quality, and fish and wildlife needs. Ultimately, this framework can be used to consistently and transparently quantify when, where and how much water is needed to achieve critical functions in upland rivers and wetlands as well as GSL itself; in other words, how we can 'have our lake and drink it too'?

Study Area

GSL basin is a densely populated semi-arid region in the western US, characterized by competition for limited water resources and vulnerable aquatic ecosystems. Water development, diversions, and consumptive uses have greatly reduced streamflow and altered its timing throughout the basin. Lake level has consequently declined by 51% since European settlement (Null and Wurtsbaugh 2020), reaching a record-low in 2022 (Great Salt Lake Strike Team, 2025). Dry playa now separates GSL peripheral wetlands from the wetted body of the lake (Null and Wurtsbaugh 2020, Figure 1), and managers rely on control structures to manage water levels in impounded wetlands for emergent vegetation habitat (Downard et al. 2014). The basin's river, wetland, and lake ecosystems face mounting stressors (Hassan et al. 2023) including recurrent and prolonged drought, rapid population growth and related land use changes (Zesiger et al. 2023), invasive species expansion (Kettenring et al. 2012, 2020), and consumptive water uses that are too high to support healthy ecosystems (Great Salt Lake Strike Team 2025; Wurtsbaugh et al. 2017; Low and Downard 2018).

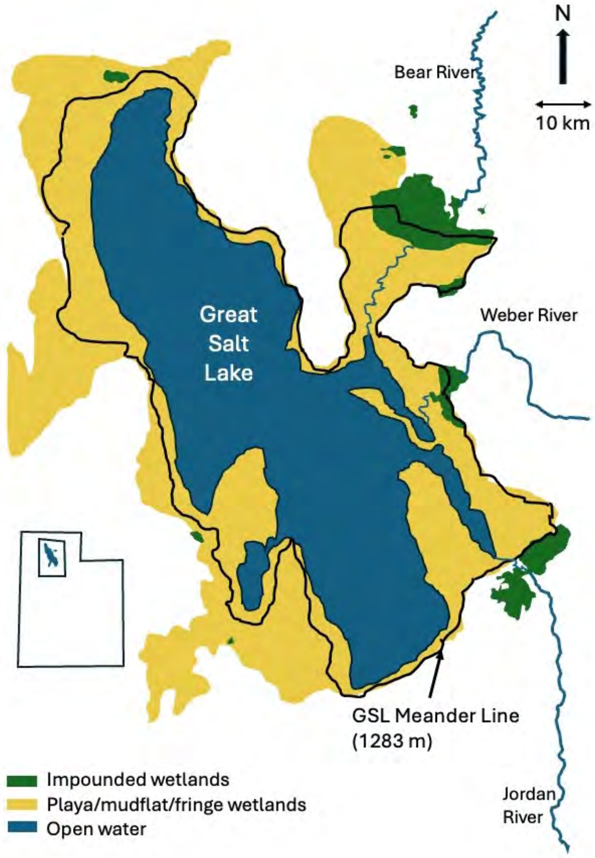

FIGURE 1. MAP OF GREAT SALT LAKE (GSL), INCLUDING MAJOR CONTRIBUTING RIVERS AND IMPOUNDED WETLANDS. THE MEANDER LINE DELINEATES GSL'S HIGH WATER BOUNDARY.

Maintaining adequate environmental water in GSL basin streams and wetlands supports healthy fish and wildlife populations, generating considerable economic benefits and providing management flexibility by allowing Utah to retain wildlife management authority (UWAPCT 2025). Three river systems - the Bear, Weber, and Jordan rivers - are the primary tributaries to GSL (Figure 1). These rivers originate in the Uinta and Wasatch Ranges, with steep-gradient mountain systems that transition to broad valley systems downstream. Mountain snowmelt is the main source of streamflow (Turney et al. 2025a). These basins support populations of Bonneville Cutthroat Trout (*Oncorhynchus virginalis*), June sucker (*Chasmites liorus*; Provo River), and Green Sucker (*Pantosteus virescens*; Bear and Weber rivers), which are species of conservation focus (UDWR 2019; UWAPCT 2025). Altered streamflows, thermal regimes, degraded physical habitat, competition and hybridization with nonnative species, and habitat fragmentation threaten these species (Budy et al. 2007; Goodrum et al. 2025).

Historically, the deltas of these rivers supported vast areas of wetlands characterized by diverse native pondweed and bulrush habitats adapted to natural seasonal fluctuations in streamflow and lake level. However, after European settlers began channelizing these areas and extensively diverting river flows for irrigated agriculture, these wetland habitats – and the migratory bird populations they supported - began to diminish, and water quality conditions also suffered. Spurred by die-offs caused by avian botulism in the early 1900s (Adams, 2025), concerned duck hunters and conservationists worked to purchase and protect wetland areas around the lake (Frank et al., 2016). These areas include the federal

Bear River Migratory Bird Refuge at the mouth of the Bear River (established 1928), and state-owned waterfowl management areas at the mouths of the Weber and Jordan Rivers (established 1937 and 1935, respectively).

These protected areas were impounded in order to maintain wetland habitat and protect water quality despite reduced river inflows (Downard et al. 2014). While the control structures of these impounded wetlands (e.g., dikes, berms, culverts) do not allow for the natural hydrologic fluctuations that can occur in unimpounded wetlands and upstream rivers, they provide critical breeding, nesting, and foraging habitat for significant populations of waterfowl and shorebirds, and serve important functions related to nutrient cycling and water purification (Utah DEQ 2018; Wood and Baker 2023). Notably, GSL wetlands provide vital habitat for as many as 12 million migratory birds, including the Wilson's phalarope (*Phalaropus tricolor*), which is being evaluated for potential listing under the Endangered Species Act (Great Salt Lake Strike Team, 2025). The altered hydrologic regime has been identified as one of the greatest threats to the health of GSL wetlands (Utah DWQ 2016).

Deliberate adjustment of water levels in impounded wetlands can be an effective tool for managing wetland ecosystems (Downard et al. 2014). Water levels are variable in natural wetlands, creating the varied soil conditions and plant communities that make wetlands important wildlife habitat. Human management of water levels, as done for GSL impounded wetlands, attempts to mimic key aspects of these natural fluctuations to support desired ecological functions while balancing other management goals. For example, changing water levels can encourage beneficial plant communities (Downard et al. 2017) or increase diversity among existing plants. Water levels can also be manipulated to treat unwanted vegetation through flooding or through dewatering (Rohal et al. 2025), which allows access for other methods of control (Kettenring et al. 2020) .

Because of GSL's economic and environmental importance, Utah is making historic water law revisions, policy changes and investments to stretch water supplies for continued agricultural production and anticipated population growth, while increasing streamflows to GSL to reverse lake decline. In 2020, the Utah legislature passed a water banking act which allows water right holders to voluntarily lease water on a temporary or permanent basis, including to instream flows (S.B. 26). In 2022, Utah expanded the definition of beneficial use of water to include sovereign lands like GSL (H.B. 22). Other recent efforts include the initiation of a GSL Basin integrated planning process (H.B. 429), creation of a GSL watershed enhancement trust (H.B. 410), watershed council (H.B. 161), Commissioner's office (H.B. 491), and a more coordinated focus by the state's Department of Natural Resources (H.B. 520).

Methods

Characterizing functional flows for GSL basin's rivers and wetlands

Functional flows were characterized for both GSL basin's rivers and wetlands, where a functional flow refers to a seasonal component of the natural hydrologic regime that provides distinct ecological, geomorphic, and/or biogeochemical functions (Yarnell et al. 2020). To develop functional flows for rivers, we reviewed the functional flows and flow metrics identified for California (Yarnell et al. 2020, Patterson et al. 2020) and revised them to reflect the semi-arid, snowmelt-dominated hydrology and species of management concerns in the GSL basin. We further reviewed the literature review of established relationships between seasonal and interannual hydrologic patterns and functions relevant to river and impounded wetland ecosystems for the region. Then we organized two stakeholder workshops to solicit feedback and build consensus on ecological management goals and functional flows for GSL basin rivers (February 2024) and wetlands (September 2024). We identified around 150 stakeholders that represented a diverse array of federal, state, and local organizations and agencies (Table 1). Participants had expertise in water resource management, engineering, watershed science, water quality, aquatic ecology, avian ecology and fisheries biology. During these workshops, participants were asked to provide feedback and identify gaps in our proposed set of functional flows and hydrologic metrics. Ultimately, we integrated outcomes from our literature review and workshop input to characterize broadly relevant ecological management goals and ecosystem functions of GSL basin's rivers and wetlands that depend on specific aspects of seasonal and interannual hydrologic variability.

Table 1. Stakeholder groups that participated in the February 2024 streams (s) workshop and/or the September 2024 wetlands (w) workshop for developing GSL Basin functional flows.

Federal Agencies	**Utah State Agencies**	**Water Management Entities**	**Non-governmental Organizations**
U.S. Geological Survey (s)	Utah Geological Survey (s,w)	Canal Companies (s)	Trout Unlimited (s)
U.S. Forest Service (s)	Division of Water Quality (s,w)	Water User's Associations (s)	National Audubon Society (s,w)
U.S. Bureau of Reclamation (s)	Division of Wildlife Resources (s,w)	Local Department of Public Utilities (s)	The Nature Conservancy (s,w)
U.S. Fish and Wildlife Service (w)	Division of Water Resources (s,w)	Water Districts (s,w)	Utah Waterfowl Association (w)
	Division of Forestry, Fire and State Land (s,w)		
	Great Salt Lake Ecosystem Program (w)		
	Great Salt Lake Commissioner's Office (w)		

Quantifying functional flows for GSL basin's rivers

Identifying Reference Stream Gages

A first step in quantifying natural ranges of flow metrics that sustain ecosystem functions is identifying reference stream gage sites with minimally disturbed hydrologic conditions. We used a multiple step screening process, based on the approaches of Falcone et al. (2010) and Zimmerman et al. (2018), to select a set of U.S. Geological Survey (USGS) streamflow gages in the GSL basin that meet these criteria. Specifically, the following steps were taken:

1. Identify all active and discontinued USGS gages;
2. Eliminate gages not located on natural streams;
3. Eliminate gages that lacked at least 1 full water year of data during the 1951-2023 water year (October 1 through September 30) analysis period;
4. Eliminate gages with high relative values of a composite index calculated from 8 indicators of hydrologic disturbance ((i) percent of basin with row crop or pasture land cover from NLCD 2001, (ii) percent of basin stream lines classified as "artificial path", (iii) percent of basin flow lines classified as "ditch" or "canal" or "pipeline", (iv) number of major National Pollutant Discharge Elimination System (NPDES) discharges in basin, per square km, (v) Number of major dams in basin, per square km, (vi) road density in basin, (vii) total freshwater withdrawal in basin,and (viii) change in reservoir storage from 1950-2000);
5. Eliminate gages affected by dams or diversions by checking remarks in USGS Annual Water Data Reports, reviewing the National Inventory of Dams, and inspecting satellite imagery; and,
6. Assess remaining candidate gages and periods of record with local experts, including staff at the Utah Departments of Environmental Quality and Natural Resources, Utah State University, and the USGS to ensure they represent minimally-disturbed reference hydrology.

To assess how well the identified reference gages represent GSL basin streams more broadly, we compared the distributions of key geospatial attributes known to influence hydrology (basin area, mean basin elevation, average precipitation, catchment average annual temperature, and groundwater recharge) between the reference gages and 10,269 km stream network across the basin.

Calculating Functional Flows

Given the inherent challenge of deterministically or visually identifying functional flows for many stream gages and years, we used a repeatable and transferable timeseries signal-processing approach to calculate the flow metrics. Similar to the approach taken by CEFF (Patterson et al. 2020) and numerous other large-sample hydrology studies (e.g., Tarasova et al. 2018; Canham et al. 2025), this method relies in part on expert understanding to define seasonal start timings. Annual functional flow metrics were calculated from daily average streamflow time series using fully automated python-based signal processing methods from code that is publicly available on Github (*https://github.com/USU-WET-Lab/utah-func-flow*). Specific parameters and their values are included in Table S1.

The general approach to calculate seasonal flow start timing metrics is as follows and detailed in Patterson et al. (2020): A high standard deviation Gaussian filter was applied to daily average streamflow time series to detect dominant peaks and valleys from the annual hydrograph. Localized search windows were set around hydrologic features of interest (e.g., annual peak flow). A low standard deviation Gaussian filter was then applied to the observed daily flow in the search window to identify seasonal shifts in the hydrograph, based on slope breaks in the derivative of a fitted spline curve. Break points were used to quantify the annual start timing of the high flow ascension, high flow recession, and summer low flow, from which seasonal magnitude, duration, frequency, and rate of change metrics could then be calculated.

To capture the specific functional flows identified for GSL basin rivers, we developed a functional flows calculator by adapting the methods detailed in Patterson et al. (2020) and Appendix C of the CEFF guidance document (California Environmental Flows Working Group 2021). Summer low flow spans the annual start timing of summer low flow to October 15 to align with typical irrigation schedules and seasonal temperature changes. Winter low flow ranges from October 16 to the start timing of high flow ascension. The high flow component (black box in Figure 2 top panel) encompasses the high flow ascension, peak flow, and high flow recession. The high flow recession rate was calculated as the median daily rate of change in flow from the start date of the high flow recession until the start of the summer low flow period, considering only days with negative change to omit storm events during the recession period. Conversely, the high flow ascension rate of change was calculated as a median daily rate of change in which only positive-change days were considered. Peak flow magnitude was calculated as the 2-year recurrence flow (50th percentile exceedance value of annual maximum series) for gages with 5 or more water years of flow data (no longer recurrence interval events were evaluated due to gage record length constraints). The peak flow duration (cumulative number of days above 2-year flow magnitude) and frequency (number of times the 2-year flow magnitude is exceeded) were calculated in years where the 2-year recurrence flow occurred.

Evaluating Functional Flows

An assessment of the functional flows calculator was conducted by measuring the accuracy of the seasonal flow timing metrics (start of high flow ascension, start of high flow recession, start of summer low flow) across all reference gage - years through a systematic visual inspection and statistical analysis. The timing metrics largely determine the accuracy of the full suite of functional flow metrics because other seasonal metrics are calculated based on the seasonal flow timing. Thus, performance of the timing metrics is reflective of the entire suite of functional flow metrics. The performance assessment followed an abbreviated version of the methods used by Patterson et al. 2020. As the algorithm developed here was adapted from a previous algorithm calibrated to similarly snowmelt-dominated hydrology, a simpler performance assessment was deemed sufficient. First, functional flow timing metrics were overlaid on the annual hydrograph and visually assessed. Common inaccuracies in timing were categorized and tabulated, including seasonal flow timing set early or late by more than two weeks, or missing timing. These tabulated errors represent cases in which the metric values did not accurately reflect the observed hydrology. The occurrence rate of observed errors was calculated as a percentage. An accuracy of 90% was deemed an acceptable error tolerance for each functional flow metric, and any error rates greater than this were addressed through iterative modifications to the algorithm before finalizing the performance assessment and generating results. For instance, in the initial visual assessment, early high flow start timing was noted at selected sites. High flow start timing can be challenging to pinpoint accurately because it may be caused by a variety of factors including variable spring rainstorms or rain-on-snow events, increase in baseflow, or snowmelt runoff due to temperature rise. To correct this issue, the algorithm was adjusted to require a higher relative magnitude threshold until accuracy reached 93%.

The non-parametric Kruskal-Wallis and post hoc Dunn tests were used to determine if the seasonal flow timing metrics (start of high flow, start of high flow recession, start of summer low flow) were statistically distinct ($p<0.05$) across reference gage-years. Statistically distinct timing metrics would also provide additional confirmation of timing metric accuracy and serve as a supplement to the visual inspection of the functional flows calculator described above. Because water allocations and instream flows often vary by water year type (Null & Viers 2013) and because native species have adapted to natural hydrologic variability (Poff et al., 1997), the Kruskal-Wallis test was also used to assess if functional flow metrics were statistically distinct with respect to water year types. Each water year in the study period (WY 1951-2023) was classified into one of three water year types: dry, moderate, and wet (Table S2) based on terciles of the annual runoff summary index time series published by the USGS for the Great Basin Water Resource Region (region 16) (USGS, 2024). Finally, to better understand how the functional flow metrics relate to watershed properties, seasonal flow start timings were plotted with respect to the same year's average spring temperature and other climate and watershed attributes linked in the literature to snowmelt-dominated hydrology (e.g. air temperature, elevation), both for individual gages and across reference gages.

Estimating functional flows for GSL impounded wetlands

Due to resource constraints, we did not calculate wetland functional flow metrics explicitly as was done for rivers. Instead, we proposed hydrologic metrics that could be important to consider when quantifying the functional flows identified for GSL managed wetlands. In these managed wetlands, acceptable metric values and their ranges are highly dependent on site and season specific management objectives that are area dependent within each managed wetland complex. Future opportunities to more quantitatively evaluate wetland functional flows are considered in the discussion.

Results

A functional flows framework for GSL basin rivers and wetlands

Key environmental management goals for GSL basin's rivers identified by the stakeholder workgroup include to: support movement and life cycle processes of fish/aquatic life; protect water quality; support geomorphic processes that sustain complex physical habitat and maintain flood resilience; connect stream channels longitudinally and with their floodplains; and support healthy riparian vegetation. We identified five functional flows broadly supportive of these goals: winter low flow, high flow ascension, high flow peak, high flow recession, and summer low flow (Figure 2 top panel, Table 2). We also considered summer monsoonal flow but determined that, while it is a functional flow in other Utah basins, it does not play as a large role in the GSL basin. Winter low flow spans the end of irrigation season (defined as October 16 herein) to the start of the high flow ascension. It provides stable habitat for fall spawning species and egg development and maintains macroinvertebrate abundance and diversity. The seasonal high flow period is represented by three related functional flows: high flow ascension, peak, and recession. High flow ascension is the period when flows begin to substantially increase with snowmelt until flows begin to substantially decrease at the start of high flow recession. Both high flow ascension and recession are characterized by their annual timing, duration and rate of change. Flow ascension is important for fish migration and spawning cues and accessing the floodplain. The high flow peak promotes increased longitudinal connectivity, groundwater recharge, and erosional and depositional processes that clean spawning gravel, support riparian recruitment, maintain complex habitat, and inhibit non-native fish and plants via disturbance. Flow recession is important to provide suitable habitat for migration, spawning and juvenile rearing for species of management interest, and sediment deposition. Summer low flow is the period when flows stabilize following the high flow recession through the end of irrigation season in fall. Summer low flow patterns (i.e., start timing, magnitude, and duration) maintain water quality, including aspects such as healthy water temperature and dissolved oxygen, limited harmful algal blooms, and nutrient cycling. Summer low flows also support instream habitat during stressful dry periods, enable movement of native aquatic species, and maintain channel capacity and flood resilience by limiting vegetation encroachment. Table 2 provides more detailed evidence and citations for these and additional connections.

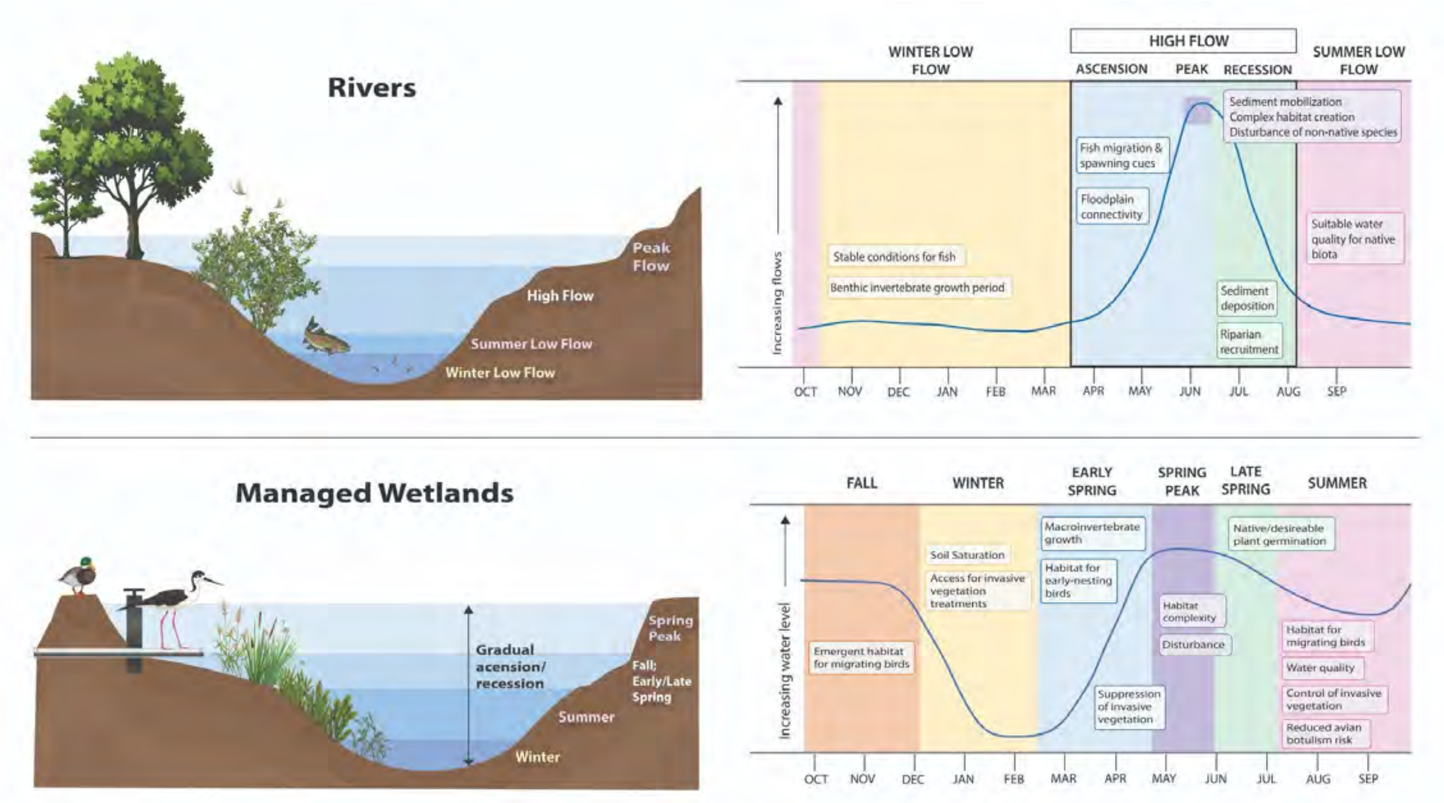

Figure 2. Generalized Functional flows (colored boxes on right) for rivers (top panel) and managed wetlands (bottom panel) in Utah's Great Salt Lake Basin, with important ecological functions identified. These are hypothetical hydrographs highlighting major Flow/Water stage characteristics and associated ecological functions. We note that the specific hydrograph shapes and functions will vary across years and locations based on the climate conditions, habitat needs and specific management goals.

Table 2. Great Salt Lake Basin functional flows for streams (s) and wetlands (w), ecosystem functions, and management goals supported by specific functional flow components. Co-developed with local experts. Numbered citations of relevant scientific literature and specific flow characteristics (M=magnitude, T=timing, D=duration, F=frequency, R=rate of change) are also included, with numbered citation references in Supplemental information.

Functional Flow Component	Stream (s) and/or Wetland (w)	Ecosystem Function	Ecological Management Goal
Winter Low Flow	s	Increase flow and water temperature to minimize frazil and anchor ice development [1]	Protect water quality

Functional Flow Component	Stream (s) and/or Wetland (w)	Ecosystem Function	Ecological Management Goal
	s	Cue fall spawning [2,M,T]; Provide stable flows for fall spawning and egg development [3]	Support movement and life cycle processes of fish/aquatic life
	s,w	Maintain macroinvertebrate abundance and diversity [4,M; 5]; Draw down wetland water levels to protect infrastructure and enable phragmites and carp control (late winter)	Sustain and help recover native aquatic species and wetland plants
	w	Fill ponds for waterfowl hunt (early winter); Saturated soils to enable rapid pond refill in spring	Sustain and support waterbird populations
High Flow Ascension	s	Cue fish spawning [6,T; 7; 8; 9]	Support movement and life cycle processes of fish/aquatic life [5,M]
	s	Increase longitudinal connectivity; Connect to water table/support groundwater recharge [8; 10,M,D,R; 11]	Connect stream channels longitudinally and with their floodplains
	w	Increase wetland water levels gradually and early to provide habitat for early-nesting/migrating birds, support macroinvertebrates growth, limit sedimentation, and limit phragmites germination [12]	Sustain and support waterbird populations; Sustain and help recover native wetland plants
High Flow Peak	s,w	Scour/flush periphyton/sediment [7; 8; 9]; Maintain/rejuvenate deep pools and complex habitat; Deposit sediments in floodplains/large wood in channel; Limit vegetation encroachment; Maintain/create side channels and backwaters [13,M; 14,M; 15,M,T,D; 16]	Support geomorphic processes that sustain complex physical habitat; Sustain and support waterbird populations
	s	Clean spawning substrate; Enable fish movement/migration [6,T,M; 7; 8; 16,T,D,M; 17,M; 18]	Support movement and life cycle processes of fish/aquatic life [6]
	s	Inundate riparian zone; Support plant biodiversity via disturbance, riparian succession, extended floodplain inundation [8; 14,M,D; 15; 19,M; 20,T]	Support healthy riparian vegetation [14]
	s	Increase longitudinal connectivity; Increase lateral connectivity with floodplain; Support groundwater recharge [10,M,D,R; 16,M]	Connect stream channels longitudinally and with their floodplains
	s,w	Inhibit non-native fish and plants via disturbance [8; 13; 20,T; 22,M]	Support and help recover native species [38,39]
	w	Inflows sufficient to flush key wetland habitats without flooding areas that could later become botulism hotspots [12]	Protect water quality

Functional Flow Component	Stream (s) and/or Wetland (w)	Ecosystem Function	Ecological Management Goal
High Flow Recession	s	Limit channel encroachment; Sediment sorting/transport/size selective deposition; Increase habitat diversity [21; 22,M]	Support geomorphic processes that sustain complex physical habitat
	s	Promote larval transport and egg development; Support fish and amphibian spawning [9; 22,T] and juvenile fish rearing in slow velocity habitats	Support movement and life cycle processes of fish/aquatic life
	s,w	Support riparian recruitment [22; 23; 24,T,R]; Maintain appropriate flood depths to enable native wetland plant germination [25; 26; 38; 39]	Support healthy riparian vegetation; support and help recover native wetland plants
	s	Increase lateral connectivity; Support groundwater recharge [10,M,D,R]	Connect stream channels longitudinally and with their floodplains
	s	Increase general species biodiversity [27; 28,T,R,D]	Sustain and help recover native species
Summer Low Flow	s	Maintain healthy water temperature and oxygen; Minimize harmful algal blooms and algae; Dilute and promote uptake of sediment, nutrients, pollutants [8; 18; 29; 30; 31]	Protect water quality
	s	Limit vegetation encroachment; Maintain channel capacity [13,M]	Support geomorphic processes
	s	Maintain habitat for fish; Support movement of fish/aquatic life [4]; Support primary and secondary producers [3; 8; 22; 27; 28,M; 31; 32]	Support movement and life cycle processes of fish/aquatic life [32]
	s	Maintain riparian soil moisture [13; 34,M,R]	Support healthy riparian vegetation
	w	Maintain water levels to provide habitat and enable effective phragmites control [35; 36; 37,M,T; 38; 39]	Sustain and support waterbird populations; Sustain and help recover native wetland plants
	w	Late summer water level increase to buffer pollutants, limit botulism, provide habitat for migrating birds [35,M,T]	Protect water quality; Sustain and support waterbird populations

Environmental management goals guiding water level adjustments in GSL impounded wetlands, as identified through our stakeholder workshops and past studies (e.g., Utah DEQ, 2018), include protecting water quality; sustaining and supporting waterbird populations; supporting and recovering native wetland plants (Table 2). We identified six functional flow periods during which wetland water levels can achieve specific ecological and biogeochemical functions associated with these management goals: fall, winter, early spring, spring peak, late spring, and summer (Figure 2). In the fall, high water levels provide emergent habitat for migrating birds. Steady drawdown over winter maintains soil saturation while allowing access for control of unwanted vegetation. During early spring, gradually increasing water levels provide breeding habitat for migrating waterbirds, support macroinvertebrate growth, and limit non-native vegetation establishment. During the spring peak, high water levels create habitat complexity and flush stagnant water and organic matter. Not overtopping water infrastructure is also critical to reducing potential for botulism hotspots that can affect bird populations. In late spring, gradually receding water levels support germination of desired native vegetation. In summer, sufficiently high and stable water levels provide emergent habitat for migrating birds, help maintain healthy water quality, and support effective treatment of invasive vegetation.

The timing of functional flows for rivers and impounded wetlands is related but somewhat offset (Figure 2), reflecting the highly managed state of the wetlands and ecological management goals related to both native and desired species in the context of other management objectives such as limiting invasive vegetation (Rohal et al. 2025; Kettering et al. 2020). In spring, the high flow component in rivers - the spring ascension, peak, and recession periods - occur around a month later on average than the associated functional flow periods in downstream wetlands - early spring, spring peak, and late spring periods. The earlier spring gradual increase in wetland water levels supports early nesting birds and limits invasive vegetation, while the earlier recession supports germination of desirable emergent vegetation. Both river and wetland flows/water levels generally diminish from late spring through summer, fall and winter, supporting an array of ecological functions. However, wetland water levels may be temporarily increased in fall to provide emergent habitat for migrating birds, or to manage invasive - desired plant dynamics (Rohal et al. 2025; Kettering et al. 2020). The magnitudes of the functional high flow peak and summer/winter low flow periods in rivers are highly variable from year to year, while the functional water level ranges in wetlands during both spring peak and winter periods are much smaller.

Quantifying functional flows for GSL basin rivers

Reference stream gages

We identified 35 reference gages in the GSL basin (Figure 3a, Table S3) with 516 total reference gage - years from water years 1951 to 2023, and 1 to 60 years of data at each gage (average 15 years) (Figure 3b). Most of these gages are located on streams draining the Wasatch mountain range, with contributing areas spanning 9 to 296 square km and mean basin elevations spanning 1,943 to 3,145 meters (Figure 3c). Relative to the basinwide stream network, reference gages are located in higher-elevations with smaller drainage areas, higher mean annual precipitation, and lower average air temperatures, as expected, given that headwater systems are generally less impaired than those near valleys and population centers.

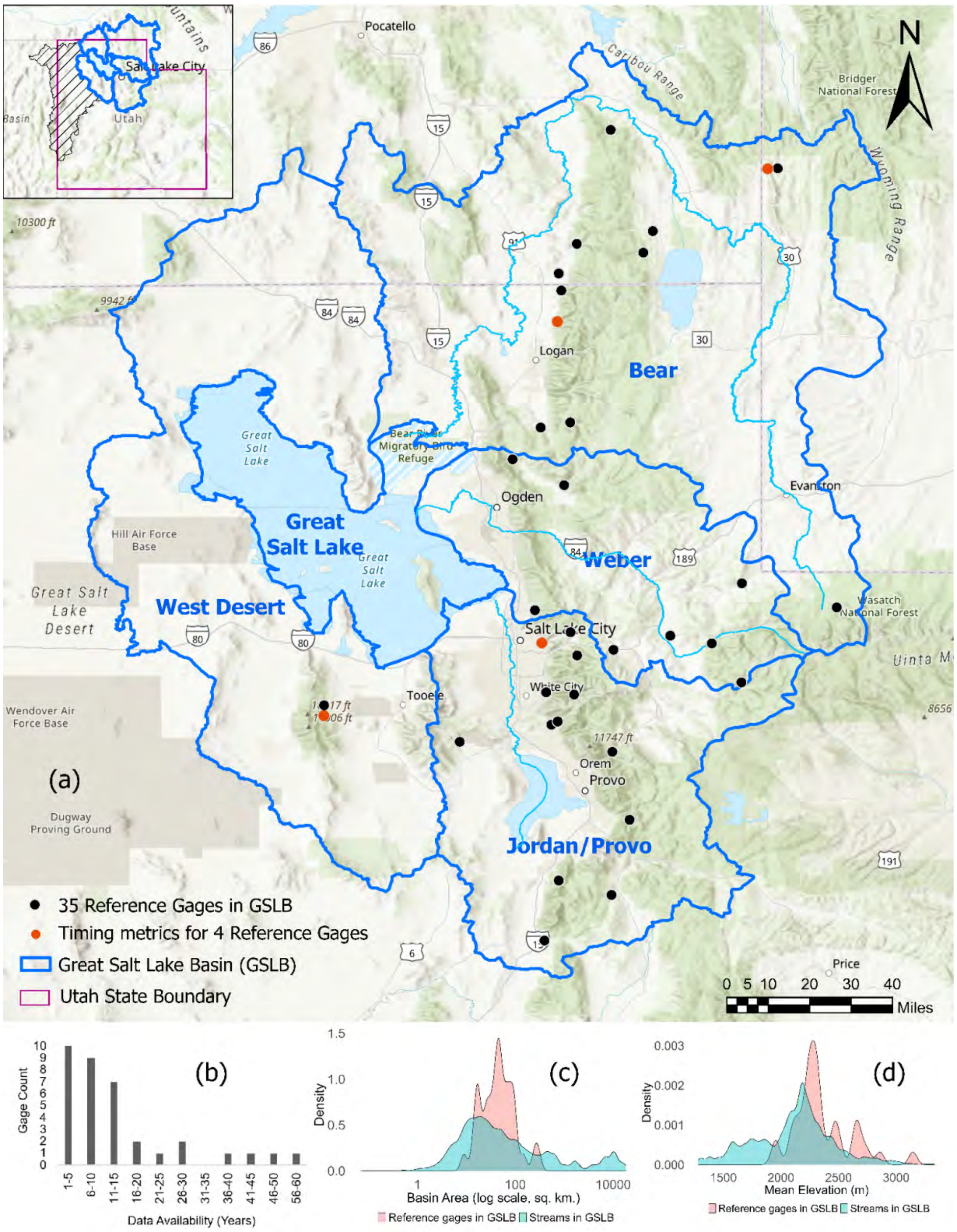

FIGURE 3 (A) GREAT SALT LAKE (GSL) BASIN AND 35 REFERENCE GAGES, (B) HISTOGRAM OF THE NUMBER OF YEARS OF REFERENCE-CONDITION STREAMFLOW DATA ACROSS 35 REFERENCE GAGES IN GSL BASIN, (C AND D) KERNEL DENSITY PLOTS OF BASIN AREA AND MEAN ELEVATION OF REFERENCE GAGES COMPARED TO THE GSL BASIN STREAM NETWORK.

Functional flow metrics for rivers

18 functional flow metric values describing five functional flows (Figure 2 top panel) were calculated at each reference gage as detailed in Table 3. The automated functional flows calculator identified seasonal flow components across the range of climate and physiographic settings represented by the

reference gages (Figure 4, Figure 5). Figure 4 showcases functional flow timing metrics across a range of water year types for sites spanning distinct physiographic settings. Sites differ in terms of the prominence and timing of the high flow period, the influence of rainstorms, and baseflow contributions. All functional flow metric values for reference gages are available in Table S4. A limited number of gage-years with poor performance occurred for all three timing metrics, including early high flow start timing with the highest recorded error rate at 7% (Table S5). Other errors in timing metrics occurred less than 5% of the time. The statistically significant differences in seasonal timing metrics (Figure 5) further confirmed the ability of the functional flows calculator to accurately identify distinct hydrologic seasons from streamflow data.

TABLE 3. FUNCTIONAL FLOW COMPONENTS FOR STREAMS AND THEIR CORRESPONDING CHARACTERISTICS AND FLOW METRICS.

Functional Flow Component	Flow Characteristic	Functional Flow Metric	Description
Winter Low Flow	Magnitude	Winter median flow	50th percentile of daily flow within winter low flow period
		Winter high baseflow	90th percentile of daily flow within winter low flow period
	Duration	Winter duration	Number of days from Oct 16 to start of high flow period
High Flow	Timing	Start of high flow	Start date of high flow period
	Magnitude	High flow period low flow	10th percentile of daily flow within high flow period
		High flow period median flow	50th percentile of daily flow within high flow period
	Duration	High flow duration	Number of of days from start of high flow to start of summer low flow
High Flow Ascension	Rate of Change	Ascension rate	Median daily rate of change during ascension period; calculated only for days with positive/increasing change
High Flow Peak	Magnitude	2-year flood magnitude	50th percentile exceedance value of annual maximum daily flow series over period of record for sites with at least 5 years of data
	Duration	2-year flood duration	Total number of days in which 2-year flow magnitude is exceeded in a given water year
	Frequency	2-year flood frequency	Number of occurrences of 2-year recurrence interval peak flow within a water year
High Flow Recession	Timing	Start of recession	Start date of high flow recession in water year days
	Duration	Recession duration	High flow recession duration (number of days from start of recession to start of summer low flow)
	Rate of Change	Recession rate	Median daily rate of change during recession period; calculated only for days with negative/decreasing change
Summer Low Flow	Timing	Start of summer low flow	Start date of summer low flow in water year days

Functional Flow Component	Flow Characteristic	Functional Flow Metric	Description
	Magnitude	Summer median flow	50th percentile of daily flow within summer low flow period
		Summer high baseflow	90th percentile of daily flow within summer low flow period
	Duration	Summer duration	Number of days from start of summer low flow through Oct 15

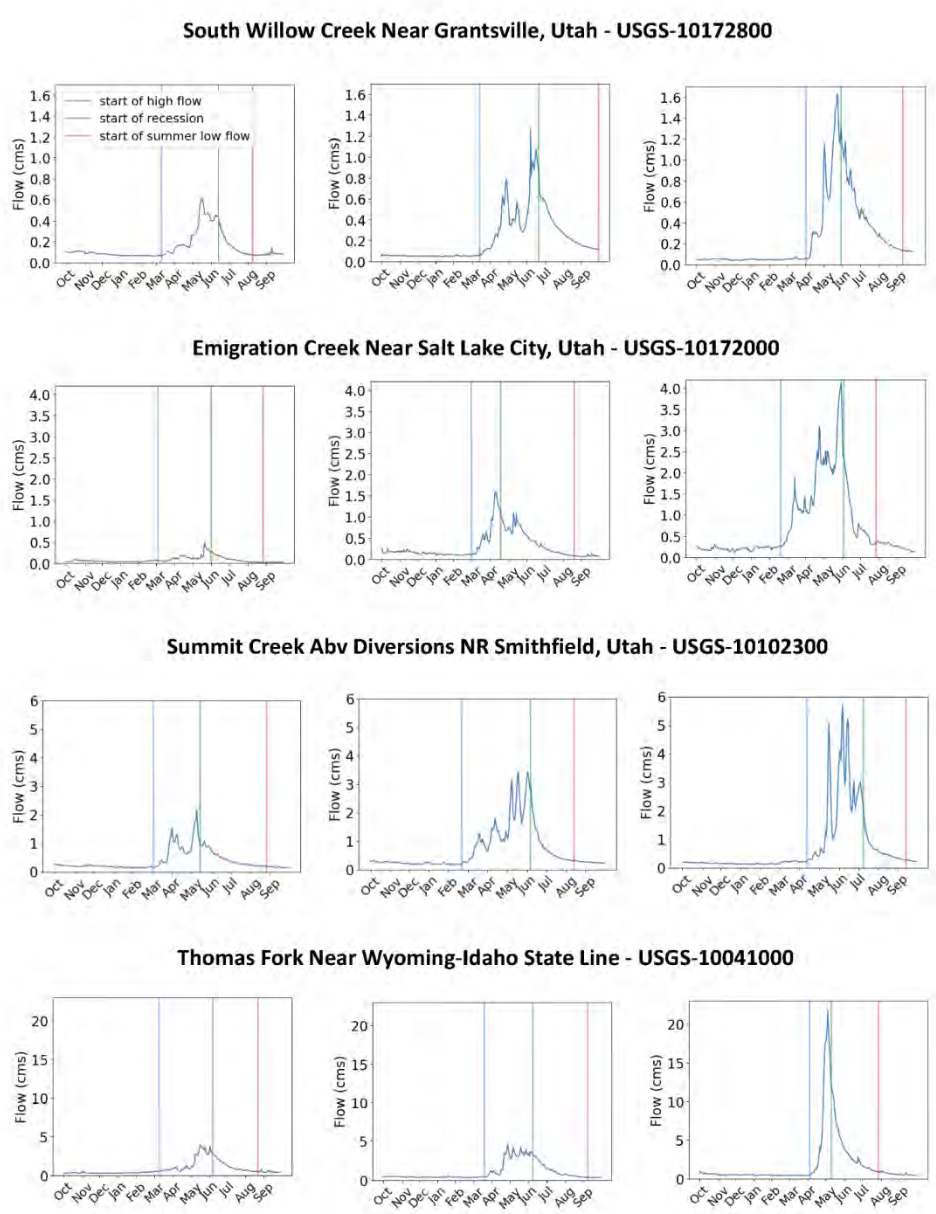

FIGURE 4. FUNCTIONAL FLOW TIMING METRICS OVERLAID ON ANNUAL HYDROGRAPHS FOR A RANGE OF CLIMATE CONDITIONS AND GEOGRAPHIC SETTINGS. GAGE LOCATIONS ARE SHOWN AS RED DOTS IN FIGURE 3.

Plots of the distributions of annual functional flow metrics provide insights into natural seasonal and year-to-year patterns of hydrologic variability (Figure 5). The median magnitude (and 10th-90th percentile) of high flow period median flow, winter median flow, and summer median flow was 1.14 mm/day (0.25 - 3.58 mm/day), 0.27 mm/day (0.06 - 0.80 mm/day), and 0.34 mm/day (0.06 - 1.13 mm/day), respectively (Figure 5a). Despite high variance across gages and water years, the start timings of high flow ascension, high flow recession, and summer low flow were all statistically distinct from one another (Table S6). The median (and 10th-90th percentile) start dates of high flow ascension, recession, and summer low flow occurred March 27 (March 2 - April 21), June 2 (May 12 - June 22), and August 17 (July 23 - September 15), respectively (Figure 5b). While the seasonal flow start timings generally shifted later from dry to wet water years, only high flow recession timing was statistically distinguished with respect to water year type (Table S6). Across sites, an earlier start of the high flow (R^2=0.41) and recession periods (R^2=0.28) was generally associated with higher average spring temperatures as well as lower basin elevations, while annual start timing of summer low flow was insensitive to climate or watershed properties (R^2=0.04) (Figure 5c). Finally, to further contextualize the overarching functional flows conceptual framework for GSL basin streams, kernel density plots of the interannual distribution of calculated functional flow magnitude and timing metrics were overlaid on an aggregated hydrograph for a single reference gage (Figure 5d).

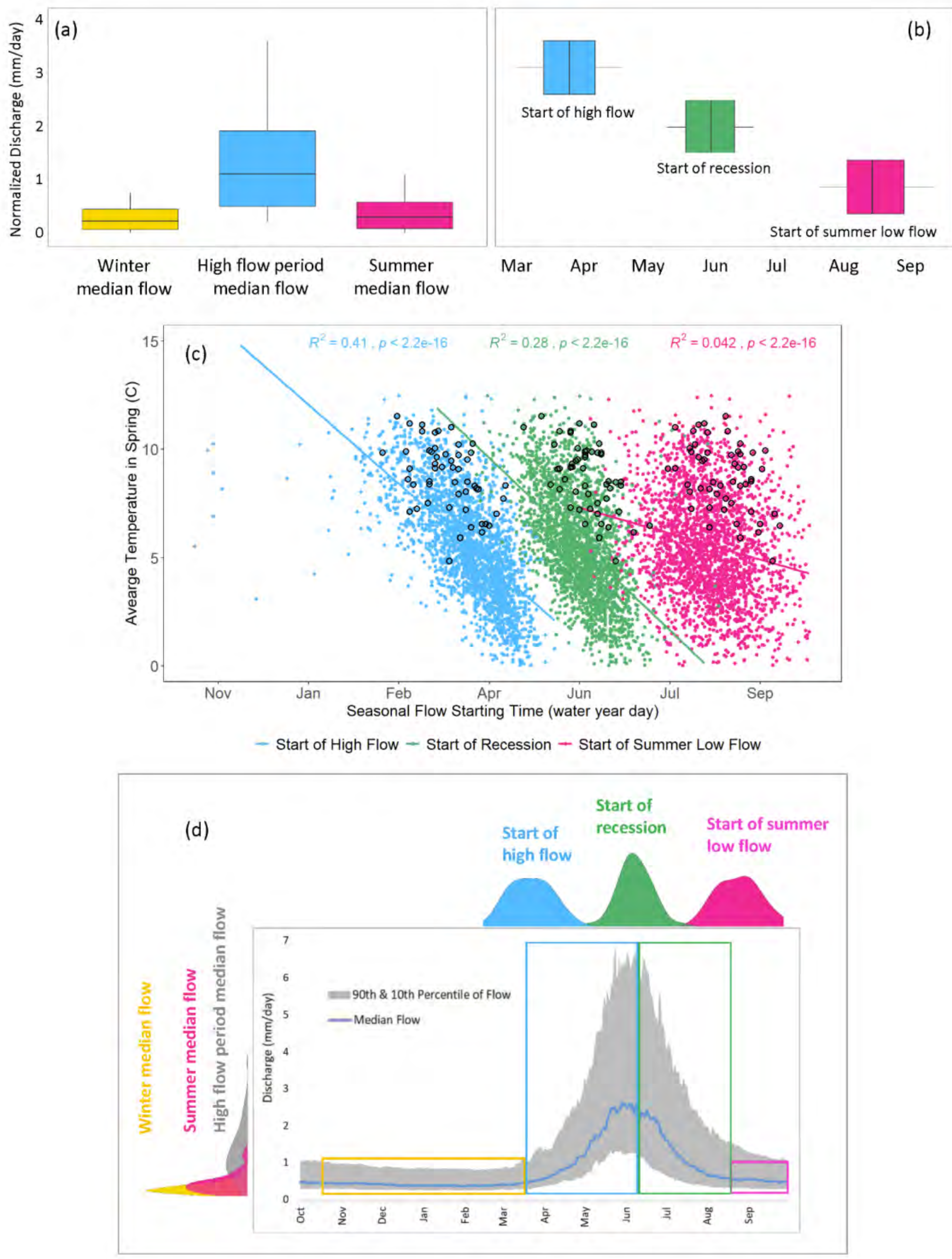

FIGURE 5. BOX PLOTS OF THE DISTRIBUTION OF FUNCTIONAL FLOW METRIC VALUES ACROSS REFERENCE GAGE - YEARS, INCLUDING (A) AREA-NORMALIZED FLOW MAGNITUDE AND (B) TIMING METRICS. (C) SCATTERPLOT ILLUSTRATING THE RELATIONSHIP BETWEEN FUNCTIONAL FLOW SEASONAL TIMING METRICS AND AVERAGE SPRING AIR TEMPERATURE. BLACK DOTS ON SCATTERPLOT REPRESENT MULTIPLE YEARS OF A SINGLE GAGE, SOUTH WILLOW CREEK NEAR GRANTSVILLE, UTAH 10172800 (RED DOT IN WEST DESERT SUBBASIN IN FIGURE 3A). (D) KERNEL DENSITY PLOTS OF FUNCTIONAL FLOW MAGNITUDE AND START TIMING METRIC VALUES OVER THE PERIOD OF RECORD OVERLAID ON THE AGGREGATE ANNUAL HYDROGRAPH FOR SOUTH WILLOW CREEK. BOXES SPAN THE MEDIAN START TIMINGS OF SEASONAL FLOW METRICS, CORRESPONDING TO THE CONCEPTUAL DIAGRAM OF GSL BASIN FUNCTIONAL FLOWS FOR RIVERS IN FIGURE 2.

Estimating functional flows for wetlands

Several hydrologic metrics are important to consider when quantifying the functional flow periods for GSL managed wetlands (Figure 2). However, the specific timing, magnitude, duration, rate of change and frequency of different water levels associated with key ecosystem functions and their interannual variability are expected to vary substantially in different wetland areas and for different species assemblages and water infrastructure settings. Important metrics in the fall period include: fall ascension start timing and ascension rate, fall stable high water level magnitude and duration. Winter period metrics include: winter recession start timing and rate, winter stable low water level magnitude and duration. Early spring through summer functional flow metrics include: early spring ascension start timing and ascension rate, spring peak water level magnitude and duration, late spring recession start timing and late spring/summer recession rate, summer water level magnitude and duration.

Discussion

Declining water levels in GSL have resulted in substantial efforts to conserve, purchase, and lease water in the name of increasing GSL water levels. These efforts offer an opportunity to shepherd water through the basin to provide environmental benefits within streams and wetlands prior to water reaching GSL. A functional flows approach to environmental water management - focused on distinct aspects of the flow regime that sustain the ecological, geomorphic, and biogeochemical functions upon which aquatic communities depend (Yarnell et al. 2015) - offers a pathway for supporting river and wetland ecosystem health in the GSL basin. By characterizing environmental water needs with respect to broadly important functions rather than species- or site-specific minimum habitat requirements, the approach is applicable across the diversity of flow regimes, ecosystems, and species of management concern occurring within the basin. Considering acceptable seasonal and interannual flow ranges based on a suite of annual hydrologic metrics, rather than prescribing specific flow thresholds, accounts for natural variability and uncertainty in flow - ecosystem linkages and increases management flexibility (Stein et al. 2021). A functions-driven approach can also accommodate altered or managed systems (e.g., impounded wetlands) and non-stationarity in environmental conditions associated with shifting climatic patterns and ecological disturbances.

Since opportunities for strategic environmental water management are relatively new in Utah, we convened stakeholder meetings to better understand the environmental water management goals and water needs of GSL basin stream and wetland ecosystems. This required first identifying key local, state and federal stakeholders with whom we convened the initial functional flows workshops and continued to share updates and solicit feedback as the framework was developed. The resulting suite of ecological management goals, functional flows and hydrologic metrics was co-developed by numerous agencies and scientists who also represent key intended users of the framework. This engagement represents an important step towards a common understanding of ecologically important components of hydrologic variability for GSL basin streams and wetlands, including linkages between water quantity, water quality, and wildlife. It also highlights outstanding research gaps and data needs to develop quantitative linkages between functional flows and their alteration and specific ecological functions.

This study identified and calculated hydrologic metrics describing seasonal streamflow conditions across a range of GSL basin river settings and climate conditions that share broad hydrologic patterns (Figure 4). Despite high variation in natural hydrologic conditions across reference gages, the functional flows calculator performed well and statistically differentiated seasonal flow timing metrics. The basin-wide suite of functional flow metrics developed for this study provide a quantitative, holistic foundation for characterizing ecosystem-supporting flow conditions across the basin.

Towards functional flows for GSL basin rivers

The functional flows calculator is publicly available and readily applicable to any river reach in the GSL basin with at least one year of daily minimally impaired streamflow data. The functional flows calculator performed well across reference stream gages spanning a range of physiographic and climate settings, and captures predictable seasonal and interannual flow patterns characteristic of snowmelt-dominated GSL basin rivers (Thurber et al., 2024; Julander and Clayton, 2018). The tool also generates annual hydrograph plots overlaid with seasonal flow timing metrics to facilitate evaluation and contextualize resulting flow metrics, as in Figure 4. The calculator uses signal processing techniques to calculate functional flow metrics from seasonal streamflow time series (Patterson et al., 2020). While it performs well in perennial streams with high seasonality (Figure 4 and 5), performance can suffer when applying the calculator to flashy seasonal streams or highly altered river systems affected by dams or diversions. To accurately estimate flow metrics in altered or less predictable settings, researchers recently developed a complementary, alternative 'flashy functional flows calculator' for California rivers that minimizes data smoothing and instead relies on the abrupt daily changes in flow dynamics to identify seasonal transitions (Carpenter and Yarnell, 2025). While the majority of GSL basin rivers are naturally seasonal, a similarly adapted approach could be incorporated into the GSL basin functional flows calculator to better capture the range of flow patterns exhibited under hydrologic alteration and in flashy ephemeral systems characteristic of the West Desert subbasin (Figure 3a).

Ongoing work to predict functional flows for stream reaches across the basin will provide consistent, ecologically protective flow ranges that can serve as environmental flow targets in the absence of more detailed environmental water needs. The hydrology and functional flow characteristics of the identified reference gages should not be considered representative of all GSLB streams. In particular, arid, lower-elevation, larger drainage area stream reaches are underrepresented by the reference gages, suggesting that alternative approaches are needed to predict functional flows in lowlands of the basin. Depending on data and resources availability, long-term daily unimpaired streamflow time series could be generated through either hydrologic modeling (at ungaged locations) or flow naturalization (at non-reference gaged locations), which could be directly input to the functional flows calculator introduced herein to calculate the full suite of functional flow metrics (e.g., Taniguchi-Quan et al., 2022). Alternatively, functional flow metrics calculated at reference gages could be used to train machine learning models to predict metrics across the stream network based on available geospatial attributes, following Grantham et al. (2022).

Connecting environmental water management for rivers, wetlands, and Great Salt Lake

Delivering water to GSL with the timing, magnitude, and rate of change needed to support river ecosystems would also give wetland managers flexibility to meet their ecological management goals. As GSL rivers and downstream wetlands have different ecological functions and management pressures, some functional flow needs overlap while others differ. Managers can direct where surface water goes–whether it bypasses wetlands or flows through them (Turney et al. 2025b)–providing opportunities to align river and wetland water needs. In wet years, providing functional flow ranges that benefit river ecosystems (i.e., earlier, more gradual flow ascension and recession than is typical of impaired systems) can give wetland managers more opportunity to achieve key functions. For wetland managers this is preferable to rapid high reservoir releases for flood risk mitigation occurring in April or later that often must be routed around wetland impoundments and delivered directly to the lake due to canal capacity constraints. However, delivering water to Great Salt Lake's water body beyond the wetlands is needed whenever water is available to increase lake level (Figure 1, Great Salt Lake Strike Team, 2025). Alternatively, in dry years, maintaining functional winter low flows for rivers would supply enough water to start increasing wetland water levels in mid-February, supporting early migrating birds (Tavernia et al. 2021).

Better estimating functional flows for GSL's managed wetlands would require quantifying the hydrologic conditions of impounded wetlands where managers are consistently able to achieve seasonal ecological management goals. Multiple years of daily water level data are required to quantify magnitude, timing, duration, and rate of change metrics. Ideally, these functional sites would have accompanying data sets of impoundment inflows to quantify river flow magnitude and timing and corresponding water levels required to maintain healthy wetland conditions. During the wetlands stakeholder workshop, wetland managers indicated that they currently rely on a 1970 study (Christiansen and Low, 1970) to estimate needed inflow volume, and that updated research would be of great value.

Functional flow metrics calculated annually for individual wetland areas could be standardized over the period of record to describe interannual variability and then normalized based on impoundment size and depth. These normalized values could then be applied to wetlands with varying shapes and sizes to provide water level management guidance for a range of climate conditions. The functional flow quantification process for managed wetlands is more complicated than for rivers, because wetland functions are related to water level but also tied to managed?? inflows that support functional water levels as well as non-flow related management goals.

Overcoming persistent barriers to environmental water management in the GSL basin

The functional flows framework introduced here has the potential to help address several persistent challenges to effective environmental water management in the GSL basin. These include: (1) coordination between programs and groups - including state natural resource agencies, water management agencies and conservation districts, and wetland managers; (2) adaptive management for interannual hydrologic variability, and (3) resource and data requirements and inefficiencies in developing site-specific environmental flow targets.

Improving coordination

Over the past decade, Utah has taken major steps to create mechanisms that provide water to GSL and reverse declining lake levels, including recognizing flows to sovereign lands like GSL and instream flows as beneficial uses of water, allowing water banks as a mechanism to voluntarily lease water, and appropriating $40 million for a GSL Trust to enhance flows to the lake. With these steps come opportunities to shape the magnitude and timing of streamflows to benefit rivers and wetlands as water is delivered to GSL. However, there has been little coordination to date in managing environmental water to support the combined needs of rivers, wetlands and the lake. Rather than focusing on inflexible daily or monthly flow targets or minimum standards, we focus on ecosystem functions and identifying opportunities to provide water in ways that can support both rivers and wetlands while allowing flexibility for human water demands. Our work fits well within current planning efforts of ensuring resilient water supply for GSL and human water uses (Great Salt Lake Basin Integrated Plan, 2024) and reaching a healthy target GSL elevation range (Steed, 2024).

Managing interannual variability

At a broad level, management strategies for GSL often emphasize the idea of simply adding water. While not wrong, this maxim overlooks the complexities of managing environmental water throughout the basin. Policy documents provide more nuance, recommending that managers take advantage of wet years, when water leases are typically less expensive (Great Salt Lake Strike Team, 2023). Leveraging wet years aligns with the functional flows approach of varying environmental water deliveries to rivers and wetlands between wet and dry years to maximize ecological benefits and mimic key aspects of natural hydrologic variability (Stein et al. 2021; Murray–Darling Basin Authority, 2025). Wet years present opportunities to support a wide range of ecological functions, such as creating larger flood pulses to move sediment in rivers and filling impounded wetlands to support emergent vegetation and bird habitat while passing water through wetlands to the lake to reduce playa dust and increase lake levels (Grineski et al. 2024). Previous research has identified pathways to deliver water from rivers to GSL (Turney et al. 2025b). Some routes bypass impounded wetlands using river channels, canals, or pipes, while others direct water through the wetlands, which may benefit those ecosystems if provided within certain ranges of timing, magnitude, rate of change, and frequency, as characterized in this study.

Hydrologic variability in the GSL basin is considerable through space and time, as reflected in the large ranges of functional flow metric values calculated across reference stream gages. In fact, the ranges are so large that most flow metrics were not statistically distinct with respect to water year type (Table S6). This suggests that basin-wide water year type runoff metrics, commonly used in Utah Lake (Stamp et al. 2008), California's Bay Delta (Gartrell et al. 2022), and other locations to guide water management, may not suffice to capture the full range of year-to-year variability in the annual flow regime. While environmental flows that vary based on water year type are helpful for allocating more water to the environment during wet years, when there is less competition from farms and communities, they likely do not go far enough to introduce variability into managed aquatic systems. Climate variables such as annual average spring temperature may be an additional predictor of seasonal patterns, as exemplified in Figure 5c and applied in Patterson et al. (2022) to assess projected climate change impacts on functional flow metrics. Alternatively, where stream gages are sparse, we could instead leverage high temporal covariance in functional flow metrics across gages (i.e., values are consistently high/low or early/late relative in a given year), as observed in the Weber River watershed standardized annual summer low flow magnitude series (Figure S1). In such cases, a single index gage (e.g., bold line in Figure S1) may be sufficient to describe the natural interannual variability in seasonal flow patterns and its linkages with time-varying ecological indicators for the watershed (e.g., fish population or water quality dynamics).

Efficiently allocating resources

A functional flows approach inherently overcomes resource requirements of site and species specific studies by developing consistent, broadly applicable streamflow-based targets. This lowers barriers to implementation of environmental flows across the basin and promotes transparency and knowledge sharing across specific applications (Stein et al. 2021). Regional or site-specific studies documenting how flows and their alteration relate to ecological indicators, such as the aquatic macroinvertebrate community (Utah Department of Environmental Quality, 2024) or fish population dynamics (Pennock et al. 2021), could provide additional evidence of functional flows effectiveness where resources permit and help prioritize flow management decisions. For instance, Peek et al. (2022) identified functional flow metrics and their alteration most strongly associated with stream health across California based on state surveyed aquatic macroinvertebrate and algal conditions.

In the context of the functional flows framework established herein, strategic site-specific studies could be performed to identify local circumstances (e.g., channel incision, invasive species) where flow target refinements are needed to achieve specific river or wetland ecological functions. In particular, experimental flow releases in rivers offer a unique opportunity to evaluate the flow characteristics required to achieve specific functions. For example, Utah Division of Wildlife Resources collaborated with the Weber Basin Water Conservancy District, Trout Unlimited and Utah State University researchers to evaluate the capacity for a spring flushing flow release from Echo Dam on the Weber River to mobilize the gravel bed, flush fine sediment, and reset aquatic vegetation growth on the river bed that establishes during the summer low flow period when flows are largely diverted for irrigation (Utah's Watershed Restoration Initiative, 2023). Given current entrenchment and hydromodification of this reach, the streamflow timing, magnitude and duration needed to achieve these functions is likely to differ from reference flow based estimates. Findings could inform functional flow targets for future managed reservoir releases in the studied reach and other stream reaches with similar hydro-geomorphic modifications.

Conclusions

The functional flows framework for the terminal GSL basin presented here provides a consistent approach to characterize and calculate ecologically protective flow ranges for rivers and wetlands spanning the full water year and considering interannual variability with limited data requirements. This is the first study to explicitly connect the water needs of connected rivers, wetlands, and lakes to support critical ecosystem functions. The framework, co-developed by university researchers, state and federal agencies, water management agencies and non-profit organizations, characterizes key environmental management goals and associated hydrology-driven ecological, geomorphic and biogeochemical functions. The functional flows calculator successfully quantifies key aspects of seasonal and interannual streamflow variability in GSL basin rivers. The publicly available calculator can be used to calculate broadly protective environmental water targets at unimpaired river locations, to generate training data to predict functional flows across the basin river network, and to assess alteration from functional flow ranges at impaired river locations.

The functional flows framework and environmental water targets can help address persistent challenges to environmental water management in the GSL basin related to coordination, adaptive management, and resource constraints and inefficiencies in developing site-specific flow targets. Considering acceptable seasonal and interannual flow ranges based on a suite of annual functional flow metrics rather than specific flow thresholds accounts for natural variability and uncertainty in flow - ecosystem linkages and increases management flexibility. A functions-driven approach is well suited to highly modified systems, where regional or site-specific studies documenting how functional flows and their alteration impact specific environmental management goals can support development of revised environmental water targets to achieve critical functions in different basin settings. Ultimately, functional flows can be used to consistently and transparently quantify when, where and how much water is needed to support healthy fish and wildlife populations in upland rivers and wetlands as it is shepherded to GSL.

Acknowledgements

This work was supported by the Great Salt Lake Integrated Basin Plan under the Utah Division of Water Resources. We wish to thank all the stakeholders that participated in the workshops underpinning this study. We also thank Dr. Karin Kettering for her thoughtful feedback on the manuscript. PT was supported by the Species Protection Account which is administered by the Utah Division of Wildlife Resources. FN was supported by a grant from the US Geological Survey Southwest Climate Adaptation Science Center (G22AC00593). SEN was also supported by Agriculture and Food Research Initiative Competitive Grant no. 2021-69012-35916 from the USDA National Institute of Food and Agriculture.

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Supplemental Information

A Functional Flows Framework for the Terminal Great Salt Lake Basin: Can we Have our Lake and Drink it Too?

Table S1. Utah Functional Flow Calculator parameters and values, organized by functional flow component. The associated code, including a Readme file with setup information, is available on Github at the link: https://github.com/USU-WET-Lab/utah-func-flow

Functional Flow Component	Parameter name	Value	Description
All	Stream_class	1	Default parameter values are set according to Stream Class
	max_zero_allowed_per_year	270	Maximum number if no-flow values allowed to calculate
	max_nan_allowed_per_year	100	Maximum number of null values allowed to calculate metrics
	min_flow_rate	1	Don't calculate flow metrics if max flow is befow this value, in
High Flow/High Flow Ascension	broad_sigma_hf	15	Large Gaussian filter to find high flow peak
	peak_sensitivity_hf	0.005	Peak detection sensitivity; smaller value detects more peaks
	wet_threshold_perc_hf	0.15	High flow ascension magnitude threshold; flow must be
	peak_detect_perc_hf	0.3	The peak identified to search before for high flow ascension,
	slope_sensitivity_hf	300	Sets sensitivity of slope requirement for high flow ascension
High Flow Recession	max_peak_flow_date_hfr	350	Maximum (latest) search date for the peak flow date
	search_window_left_hfr	20	Left side of search window set around max peak
	search_window_right_hfr	50	Right side of search window set around max peak
	peak_sensitivity_hfr	0.1	Smaller value = more peaks detected
	peak_filter_percentage_hfr	0.5	Relative flow (Q-Qmin) of HFR start must be certain
	min_max_flow_rate_hfr	0.1	If filtered max flow is below this value in cfs, automatically
	window_sigma_hfr	10	Large Gaussian filter to identify major peaks in entire water
	fit_sigma_hfr	1.3	Smaller filter to identify small peaks in windowed data
	sensitivity_hfr	0.2	0.1 - 10, 10 being the most sensitive
	min_percentage_of_max_flow_hfr	0.5	The detected date's flow must be certain percentage of the
	lag_time_hfr	4	Set final timing a set number of days past max spring peak
	timing_cutoff_hfr	138	Earliest accepted date for spring timing, in Julian Date
Summer Low Flow	sigma_low	7	Gaussian filter scalar to set amount of smoothing
	sensitivity_low	900	Increased sensitivity returns smaller threshold for derivative
	peak_sensitivity_low	0.2	Sensitivity to identify last major peak after which to search
	max_peak_flow_date_low	325	Latest julian date accepted of peak to search after for
	min_summer_flow_percent_low	0.125	Require that summer start is below this flow threshold;

Table S2. Water year types used to categorize calculated functional flow metrics for Great Salt Lake Basin reference gages. WATER YEAR =the 12 month period from October 1 of prior calendar year through September 30 of current year (e.g., 10/1/1950-9/30/1951 equals water year 1951). TYPE = relative wetness or dryness of water year based on terciles of USGS annual runoff data for the Great Basin Water Resource Region (https://waterwatch.usgs.gov/index.php?r=16&id=statesum) for the 1951-2023 analysis period.

WATER YEAR	TYPE		WATER YEAR	TYPE
1951	Moderate		1988	Dry
1952	Wet		1989	Dry
1953	Moderate		1990	Dry
1954	Dry		1991	Dry
1955	Dry		1992	Dry
1956	Moderate		1993	Moderate
1957	Moderate		1994	Dry
1958	Moderate		1995	Wet
1959	Dry		1996	Moderate
1960	Dry		1997	Wet
1961	Dry		1998	Wet
1962	Moderate		1999	Wet
1963	Moderate		2000	Moderate
1964	Moderate		2001	Dry
1965	Wet		2002	Dry
1966	Moderate		2003	Dry
1967	Moderate		2004	Dry
1968	Moderate		2005	Wet
1969	Wet		2006	Wet
1970	Moderate		2007	Dry
1971	Wet		2008	Dry
1972	Moderate		2009	Moderate
1973	Wet		2010	Moderate
1974	Wet		2011	Wet
1975	Wet		2012	Moderate
1976	Moderate		2013	Dry
1977	Dry		2014	Dry
1978	Wet		2015	Dry
1979	Moderate		2016	Moderate
1980	Wet		2017	Wet
1981	Moderate		2018	Moderate
1982	Wet		2019	Wet
1983	Wet		2020	Dry
1984	Wet		2021	Dry
1985	Wet		2022	Dry
1986	Wet		2023	Wet
1987	Moderate			

Table S3. Numbered citations of relevant scientific literature referenced in Table 2.

TABLE 2 CITATION NUMBER	**REFERENCE**
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Table S4. Reference gages located within the Great Salt Lake basin. GAGE_ID=USGS Gage Station ID; STATION_NAME=USGS Station Name; NHDV2_COMID=ComID (unique numerical stream segment identifier) from National Hydrography Dataset (NHDPlus v2); REF_BEGIN_YEAR=First complete water year of reference qualilty flow records within WY 1951-WY 2023 time period; REF_END_YEAR (to 2023)=Last complete water year of reference qualilty flow records within WY 1951-WY 2023 time period; DRAIN_AREA=Drainage area of gage (square miles); YRS_OF_DATA (to 2023)=Number of complete water years of flow data within WY 1951-WY 2023 time period.

GAGE_ID	STATION_NAME	NHDV2_COMID	LATITUDE	LONGITUDE	STATE	REF_BEGIN_YEAR	REF_END_YEAR (to 2023)	DRAIN_AREA	YRS_OF_DATA (to 2023)
10040500	SALT CREEK NEAR GENEVA, IDAHO	7899521	42.40326	-110.99	WY	WY1951	WY1951	37.6	1
10041000	THOMAS FORK NEAR WYOMING-IDAHO STATE LINE	7898907	42.40215	-111.025	WY	WY1951	WY1992	113	42
10054600	ST. CHARLES CREEK ABV DIV NEAR ST. CHARLES, ID	4471085	42.10965	-111.459	ID	WY1962	WY1966	17.4	5
10058600	BLOOMINGTON CREEK AT BLOOMINGTON, ID	4472167	42.18465	-111.426	ID	WY1961	WY1986	24	26
10072800	EIGHTMILE CREEK NEAR SODA SPRINGS, ID	4468419	42.53742	-111.573	ID	WY1982	WY1986	22.6	5
10093000	CUB RIVER NEAR PRESTON, ID	4560932	42.1402	-111.691	ID	WY1951	WY2010	31.6	38
10096500	MAPLE CREEK NR FRANKLIN ID	4560950	42.03722	-111.754	ID	WY1951	WY1952	21.2	2
10099000	HIGH CREEK NEAR RICHMOND, UTAH	4564426	41.97771	-111.745	UT	WY1951	WY1989	16.2	14
10102300	SUMMIT CREEK ABV DIVERSIONS NR SMITHFIELD, UTAH	4564446	41.86937	-111.759	UT	WY1962	WY1979	11.6	18
10104600	SOUTH FORK LITTLE BEAR RIVER NEAR AVON, UTAH	666844	41.50021	-111.817	UT	WY1967	WY1974	26	8
10104900	EAST FK LT BEAR RIV AB RESV NR AVON UTAH	665034	41.51827	-111.714	UT	WY1964	WY1986	56.7	23
10128200	SOUTH FORK WEBER RIVER NEAR OAKLEY, UTAH	10093106	40.74856	-111.22	UT	WY1965	WY1974	16	10
10129350	CRANDALL CREEK NEAR PEOA, UTAH	10093080	40.77495	-111.365	UT	WY1964	WY1973	11.8	10
10133700	THREEMILE CREEK NEAR PARK CITY, UTAH	10276858	40.72578	-111.563	UT	WY1964	WY1984	2.68	13
10137680	NORTH FORK OGDEN RIVER NEAR EDEN, UTAH	10273810	41.38966	-111.915	UT	WY1964	WY1974	6.03	11
10145000	MILL C AT MUELLER PARK, NR BOUNTIFUL, UTAH	10276722	40.86383	-111.837	UT	WY1951	WY1968	8.79	18
10146000	SALT CREEK AT NEPHI, UT	10330245	39.71301	-111.804	UT	WY1952	WY1980	95.6	29
10147000	SUMMIT CREEK NEAR SANTAQUIN, UTAH	10351594	39.92218	-111.754	UT	WY1955	WY1966	14.6	12
10148400	NEBO CREEK NEAR THISTLE, UTAH	10350726	39.87162	-111.57	UT	WY1964	WY1973	36.7	10
10152700	MAPLE CREEK NEAR MAPLETON, UTAH	10349002	40.13357	-111.507	UT	WY1965	WY1972	3.13	8
10160800	NO FK PROVO RIV AT WILDWOOD UTAH	10375912	40.37051	-111.567	UT	WY1965	WY1974	12.3	10
10166000	FORT CREEK AT ALPINE, UTAH	10328069	40.46523	-111.78	UT	WY1951	WY1955	6.55	5
10166430	WEST CANYON CREEK NEAR CEDAR FORT, UT	10327201	40.40523	-112.1	UT	WY1966	WY2023	26.8	47
10169800	MILL CREEK ABOVE ELBOW FORK NR SALT LAKE CITY, UT	10390258	40.70634	-111.69	UT	WY1964	WY1968	7.7	5
10172000	EMIGRATION CREEK NEAR SALT LAKE CITY, UTAH	10390242	40.74995	-111.813	UT	WY1964	WY1985	18.4	10
10172800	SOUTH WILLOW CREEK NEAR GRANTSVILLE, UT	10395905	40.49633	-112.574	UT	WY1964	WY2023	4.19	60
10172805	NORTH WILLOW CREEK NR GRANTSVILLE, UTAH	10395291	40.53272	-112.573	UT	WY1980	WY1992	5.38	13
10010400	EAST FK BEAR RIVER NR EVANSTON, WYOMING	7888092	40.87356	-110.784	UT	WY1974	WY1986	34.6	13
10130700	EAST FORK CHALK CREEK NEAR COALVILLE, UTAH	10093054	40.9577258	-111.11463	UT	WY1965	WY1974	35	10
10137780	MIDDLE FK OGDEN RIVER AB DIV NR HUNTSVILLE, UTAH	10274140	41.2996625	-111.73521	UT	WY1964	WY1974	31.3	11
10154000	SHINGLE CREEK NEAR KAMAS, UTAH	10092692	40.6124485	-111.11656	UT	WY1964	WY1973	8.4	10
10165500	DRY CREEK NEAR ALPINE, UTAH	10328059	40.4763388	-111.75771	UT	WY1951	WY1955	9.82	5
10167450	LTL COTTONWOOD CR @TANNER FLT CPGD NR ALTA, UT	10389690	40.5699498	-111.70076	UT	WY2004	WY2007	15.3	4
10167500	LITTLE COTTONWOOD CREEK NR SALT LAKE CITY, UT	10390276	40.5777263	-111.79799	UT	WY1964	WY1968	27.4	5
10171900	EMIGRATION CR BLW BURR FORK NR SALT LAKE CITY, UT	10389366	40.7871689	-111.71299	UT	WY1964	WY1968	5.9	5

Table S5. Functional flow calculator performance results.

Performance Metric Issue	Occurrence
Early high flow start timing	7% (34/516)
Early summer low flow start timing	4% (19/516)
Late recession start timing	<1% (3/516)
Missing high flow start timing	<1% (4/516)
Missing summer low flow start timing	<1% (2/516)

Table S6. Nonparametric Kruskall-Wallis and post-hoc Dunn statistical test results. The first table reports functional flow metric statistical differences with respect to water year type , as defined in Table S2. The second table reports statistical differences between seasonal flow timing metrics and between flow magnitude metrics, respectively.

*shading indicates Kruskal-Wallis significance; * indicates Dunn's test significant among all 3 comparisons*		
Results when categorize by water year type (dry, moderate, wet)		
	Kruskall-Wallis	
Metric	**chi sq**	**p-value**
HF_Tim	97.272	0.234
HFR_Tim	115.77	0.003561
SLF_Tim	107.34	0.3143
HF_Mag_50 (normalized)	485.64	0.2157
WLF_Mag_50 (normalized)	371.79	0.08692
SLF_Mag_50 (normalized)	421.41	0.03081*

Results for all water year types combined		
	Kruskall-Wallis	
Metric	**chi sq**	**p-value**
Timing Metrics (start of high flow, start of recession, start of summer low flow)	1359.9	< 2.2e-16*
(Summer low flow, high flow, winter low flow)	428.37	< 2.2e-16*

Figure S1. Annual series of standardized functional flow metric, summer low flow magnitude, across flow gages in the Weber River Basin are temporally correlated. In such cases, a single index gage (e.g., bold line in plot) may be sufficient to describe the natural interannual variability in seasonal flow patterns and its linkages with time-varying ecological indicators for the watershed.