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A Watershed Balance and Footprint Model to Address Water Bankruptcy: The Great Salt Lake case

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Abstract

Many watersheds face chronic water deficits that, if persistent, descend into water bankruptcy. Yet conventional water balance models overlook virtual water imports and exports that can intensify or alleviate deficits by teleconnecting watersheds. To address this gap, we present the novel and generalizable Watershed Balance and Footprint (WBF) model that tracks how the water footprint of the resident population is satisfied through blue (from withdrawals) and green (rainfed agricultural) water, originating from within the watershed or through virtual water trade. Demonstrating the WBF model for the watershed of the desiccating Great Salt Lake from 2010–2019, mean annual river flow was 2260 Mm^3, 785 Mm^3yr^{-1} below the flow needed to stabilize the lake. The annual water footprint was 2174 Mm^3, met by 1914 Mm^3 blue and 260 Mm^3 green water, with 1109 Mm^3 met internally and 1065 Mm^3 through virtual water imports. The watershed was a net exporter of 320 Mm^3yr^{-1} of virtual water. Of 1385 Mm^3 yr^{-1} total exports, 1297 Mm^3 yr^{-1} are delivered within the US and 88 Mm^3 yr^{-1} internationally, with eastern Asia as the primary foreign destination at 46 Mm^3 yr^{-1}. Conversely, net virtual water imports of 454 Mm^3yr^{-1} would be required to stabilize Great Salt Lake. An increased water footprint or reduced natural flow due to climate change would increase the net virtual water imports required.

Keywords: Great Salt Lake, virtual water trade, water bankruptcy, water footprint

Introduction

In 2026, the United Nations reported that water stress and acute disruption from water crises have descended into a structural failure of "water bankruptcy" where, in watersheds from every continent, inadequately managed water demands have exceeded supply for decades, liquidating aquifers, wetlands, glaciers and reservoirs to the point where a "return to normal" is no longer hydrologically possible [1]. Global loss of water storage in both natural lakes and reservoirs, especially in arid regions, further documents water demands continually exceeding supply [2]. After accounting for the relationship between water quality and water availability, globally, water quality degradation triples the number of watersheds facing water scarcity [3]. These and other sobering assessments [4–6] must drive a fundamental re-evaluation of water demands can be sustainably met going forward.

In pursuing this re-evaluation, the water management community needs new approaches to manage unsustainable water demands while continuing to meet the water footprints of inhabitants to support their wellbeing. Moving beyond incremental efficiency gains, water demand management increasingly becomes the central lever in rebalancing water demand with supply in watersheds approaching or already in bankruptcy [7]. In this context, it is essential to integrate analysis of water footprints and virtual water trade within a hydrological framework, elevating these concepts from their current status as measurable, but unmanaged, attributes of water-intensive activities [8] to strategic variables in deliberate management of water supply and demand.

A rich literature on quantification of water footprints and patterns of virtual water trade has emerged in this century. Hoekstra and Mekonnen [9] quantified the water footprint of humanity in 2000 as 9087 km^3. Of this total, 74% was "green" water—evapotranspiration (ET) from rainfed biomass products—and 26% was "blue" water derived from surface water and groundwater withdrawals. Agriculture accounted for 92% of the water footprint and 26% (2363 km^3yr^{-1}) of the total was embedded in international virtual water trade. Mekonnen et al. [10] cite a range of internationally traded virtual water of 960–4250 km^3yr^{-1}, far more than the 490 km^3yr^{-1} transported through inter-basin transfers (8). Additional virtual water is traded intra-nationally; for example, U.S. states trade 191 km^3yr^{-1} of predominantly green virtual water in the agricultural sector [11] and 317 km^3yr^{-1} is estimated across all sectors [12].

With the emergence of new teleconnections, such as soybean trade between Brazil and China, international virtual water trade doubled from 1986 to 2007 [13] with a near tripling from 1986 to 2022 [10]. Virtual water trade is projected to triple again by the end of the 21st century [14]. Virtual water trade saves a net 220–352 km^3yr^{-1} of water [13] and reduces water stress in watersheds lying within 85 of 104 countries studied [15].

As pivotal as these global studies are, water is managed within watersheds, and it is at that scale where water footprints and virtual water trade emerge as strategic management variables interacting with hydrologic water balances. Described as "economically invisible and politically silent" [16], virtual

water trade largely emerges from a constellation of private-sector agribusiness transactions that seldom lie within the jurisdiction of water management institutions [17]. Blue virtual water exports can intensify local water scarcity, with 16% of unsustainable water use tied to international virtual water trade [10], while virtual water imports, especially of green water, can increase the supply of water available to satisfy people's water footprints [8]. It is for this reason that building the capacity to track and manage virtual water trading has the potential to develop into a valuable strategy to avoid or renegotiate water bankruptcy by telecoupling [18] bankrupt watersheds with thriving ones through market transactions—rather than the costly and contentious development of water infrastructure. For example, reliance on virtual water imports can improve water security if multiple sources with uncorrelated supply risks are engaged [19–20].

This paper presents a novel, generalizable model that integrates a traditional water budget with virtual water trade that contributes to satisfying the water footprint of a watershed's population. It incorporates both blue and green water as well as water originating from within the watershed and beyond it as virtual water imports. It also accounts for virtual water exports.

Located in the western US, the endorheic Great Salt Lake watershed is presented as a case study for applying the model. From 2010–2019, mean annual river flow was 2260 Mm^3, 785 Mm^3yr^{-1} below the flow needed to stabilize the lake. The annual water footprint was 2174 Mm^3, met by 1914 Mm^3 blue and 260 Mm^3 green water, with 1109 Mm^3 met internally and 1065 Mm^3 through virtual water imports. The watershed was a net exporter of 320 Mm^3yr^{-1} of virtual water. Of 1385 $Mm^3\ yr^{-1}$ total exports, 1297 $Mm^3\ yr^{-1}$ are delivered within the US and 88 $Mm^3\ yr^{-1}$ internationally. Net virtual water imports of 454 Mm^3yr^{-1} would be required to stabilize Great Salt Lake. An increased water footprint or reduced natural flow due to climate change would increase the net virtual water imports required. Application of the Watershed Balance and Footprint model thus identifies and quantifies virtual water trade as an option to balance water supply and demand while meeting ecological water needs.

The Watershed Balance and Footprint Model

The watershed balance and footprint model integrates water balance variables, such as evapotranspiration (ET), with water footprints (WF) and virtual water (VW) imports and exports (Figure 1). Applying the traditional water balance:

$$Precip = ET + river\ outflow\ \pm interbasin\ transfers \pm gw\ recharge\ \pm res.storage \quad (1)$$

Where,

$$ET\ =\ ET_{ecosystem}\ +\ ET_{green}\ +\ ET_{blue} \quad (2)$$

$$River\ outflow\ =\ natural\ flow\ -\ ET_{blue} \quad (3)$$

Consumption of blue and green water originating within the watershed contributes to satisfying the water footprint of the population within the watershed. ET resulting from blue and green water exports contributes to satisfying the water footprint of populations beyond the watershed.

$$ET_{green} = VWexports_{green} + ET_{internal,green} \quad (4)$$

$$ET_{blue} = VWexports_{blue} + ET_{internal,blue} \quad (5)$$

Considering the internal and external sources of blue and green water that satisfy the water footprint of the population residing within the watershed, we define:

$$WF_{internal} = ET_{internal,blue} + ET_{internal,green} \quad (6)$$

$$WF_{external} = VWimports_{blue} + VWimports_{green} \quad (7)$$

$$WF_{total} = WF_{internal} + WF_{external} \quad (8)$$

These variables can be reorganized algebraically as needed. For example, to calculate WF_{total} using available data:

$$WF_{total} = ET_{blue} - VWexports_{blue} + ET_{green} - VWexports_{green} + VWimports_{blue} + VWimports_{green} \quad (9)$$

The Watershed Balance and Footprint (WBF) model (equations 1-9, Figure 1) is generalizable to any watershed with available data. Variance in the relative water volumes is useful in characterizing watersheds, for example, as net virtual water importers or exporters. The ratio between water footprint and precipitation or water footprint and natural flow can also serve as a water scarcity or stress indicator.

To our knowledge, no other watershed model integrates a water balance with virtual water flows. The Watershed Balance and Footprint Model is a tool for water demand management at the watershed scale. The model focuses on the municipal and industrial components of water footprint, which are satisfied with blue water, and the larger agro-forestry components, which can be satisfied with either blue or green water. Domestic and ecological water demands can only be met with internal water resources or interbasin imports. Industrial and agro-forestry demands compose the majority of water footprints and can be satisfied by either internal or external sources through virtual water imports.

Water availability, population, consumption of agricultural and industrial products, and water use efficiency control flow volumes of the water footprint for the population. The WBF model identifies virtual water trade as an option to satisfy this footprint. In this manner, the model is designed to assess trade-offs among ecological water demands (contained within river outflow from the

watershed), virtual water exports, and alternatives to effectively increase water availability, including virtual water imports, for satisfying the industrial and agro-forestry water footprint of the resident population.

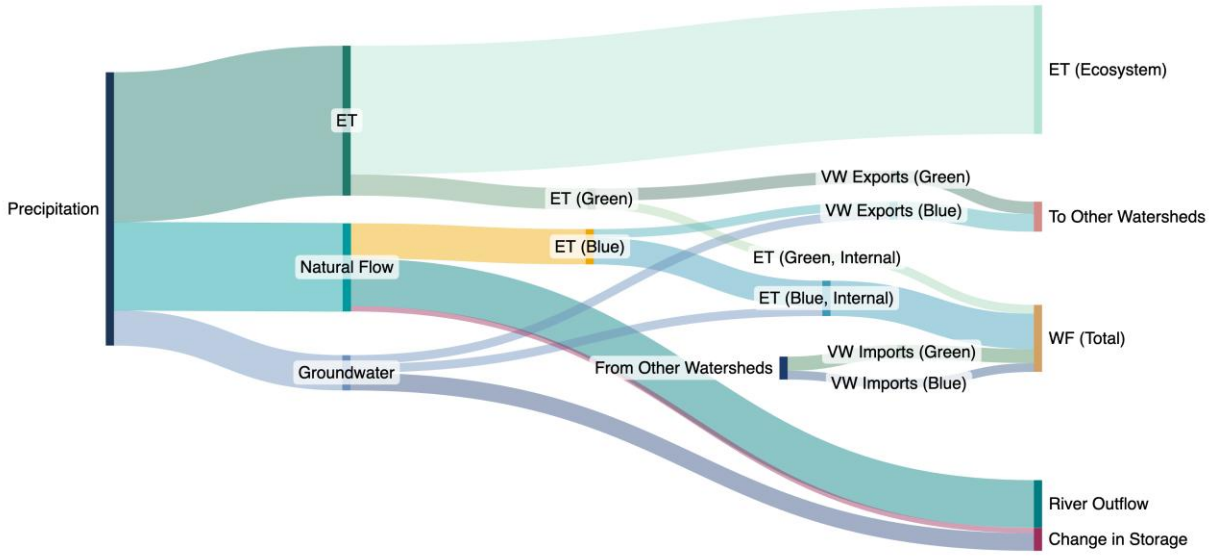


Figure 1. Generalizable Watershed Balance and Footprint (WBF) model integrating water footprints and virtual water trade with water balance. The Sankey flow lines visually reflect equations 1–9.

Results

Watershed Balance and Footprint of the Great Salt Lake Watershed

We quantified the WBF model for the Great Salt Lake Watershed spanning Utah, Idaho, and Wyoming in the U.S. Great Salt Lake is the largest endorheic lake by area in the Western Hemisphere [22] and is bisected into southern and northern bays by a railroad causeway [23]. Between the highest measured elevation in 1985–86 and the 2024–25 water year, Great Salt Lake declined from 1283.3 m to 1277.4 m elevation, well below the minimum ecological target of 1279.5 m [24], with a loss of 12.6 billion m^3 (64%) of its water volume. This exposes over 2000 km^2 of lakebed playa, generating an acute air pollution threat to the downwind population. Consequent increases in salinity threaten its unique ecosystem of brine shrimp (*Artemia franciscana*) and brine flies (*Ephydra gracilis*) that support over 10 million birds of 338 species [25]. Loss of the lake would decrease regional precipitation by 50% [26]. Economic losses would exceed 2.7 billion US dollars per year [27]. The resident population grew from 1.96 to 3.08 million from 2000–2024, and these rising municipal and industrial water demands have largely been met through urban water

conservation [28]. Thus, the watershed faces difficult trade-offs between delivering ecological water to the desiccating lake and meeting water demands from irrigated agriculture, municipal, and industrial sectors.

We estimated hydrologic flows annually from 2000–2024 for the watershed (Figure 2b) (see Methods). Annual inflows to Great Salt Lake varied greatly, from roughly one to five billion cubic meters. The Bear, Jordan, and Weber rivers provided an average of 1232, 498, and 306 Mm^3yr^{-1}, respectively. Mean total flow was 2066 Mm^3yr^{-1} (Figure 2b). River flow contributions to the lake were less than its average annual evaporation, approximately 2,126 Mm^3yr^{-1}. Annual water consumption varied from 2034 to 2678 Mm^3, with agriculture accounting for 65 percent of total consumption (Figure 2c), driven by alfalfa and hay irrigation.

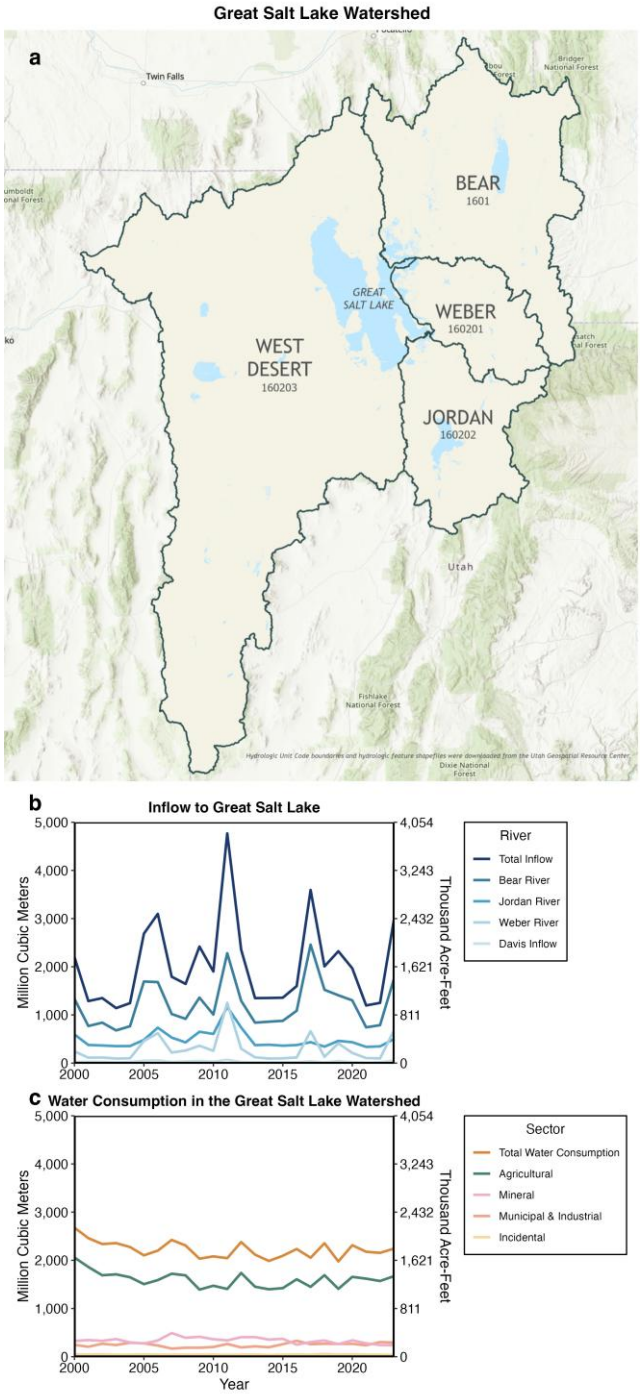


Figure 2. (a) Delineation of the Great Salt Lake watershed. (b) Inflows to Great Salt Lake [39] and (c) Watershed-wide sources of water consumption, 2000–2024 [38].

Blue and green virtual water exports and imports in animal feed, cereal grain and other agricultural products were estimated for the decade 2010–2019 (see Methods). Blue virtual water exports were 1117 $Mm^3 yr^{-1}$, 52% of total water consumption, and green virtual water exports were 268 $Mm^3 yr^{-1}$ for a total of 1385 $Mm^3 yr^{-1}$. Among agricultural sectors, virtual water exports were 1120 $Mm^3 yr^{-1}$ for animal feed (81%) and 249 $Mm^3 yr^{-1}$ for cereal grains (18%) (Figure 3a). Blue virtual water imports were 898 $Mm^3 yr^{-1}$ and green virtual water imports were 167 $Mm^3 yr^{-1}$ for a total of 1065 $Mm^3 yr^{-1}$, including 815 $Mm^3 yr^{-1}$ for animal feed, 186 $Mm^3 yr^{-1}$ for cereal grains, and 63 $Mm^3 yr^{-1}$ for other agricultural products (Figure 3a). Thus, the Great Salt Lake watershed is a net virtual water exporter of 320 $Mm^3 yr^{-1}$, including 219 $Mm^3 yr^{-1}$ of blue and 101 $Mm^3 yr^{-1}$ of green virtual water. Among agricultural sectors, the watershed was a net exporter of 305 $Mm^3 yr^{-1}$ for animal feed and 63 $Mm^3 yr^{-1}$ for cereal grains but was a net importer of 47 $Mm^3 yr^{-1}$ for other agricultural products. Blue and green virtual water exports are often embodied in the same commodities with neighboring watersheds in Utah and Idaho as primary destinations (Figure 4). Of 1385 $Mm^3 yr^{-1}$ total exports, 1297 $Mm^3 yr^{-1}$ are delivered domestically and 88 $Mm^3 yr^{-1}$ internationally, with eastern Asia as the primary destination at 46 $Mm^3 yr^{-1}$. Virtual water imports (1064 $Mm^3 yr^{-1}$) were predominantly sourced from the irrigated U.S. West and were consequently mostly blue water (Figure 5). The Great Salt Lake watershed produces proportionally few food crops, as opposed to feed crops, and relies upon imports for food.

From the components of the WBF model quantified above, the water footprint of the population of the watershed can be derived using Equation 9. Using these data, the water footprint is 2,174 $Mm^3 yr^{-1}$, composed of 1914 $Mm^3 yr^{-1}$ blue and 260 $Mm^3 yr^{-1}$ green water; 1109 $Mm^3 yr^{-1}$ is locally sourced and 1065 $Mm^3 yr^{-1}$ is imported as virtual water (Figure 6). Despite population growth from 2.41 to 2.81 million, there is no time trend to this water footprint, implying a reduction in per capita water footprint from 914 to 789 $m^3 yr^{-1}$ indicating efficiency gains in water use [28].

Ecosystem ET is a dominant water flux in semi-arid basins (Figure 6a); this water is not managed. Figure 6b integrates these results visually with a focus on management-relevant variables, including water footprint and virtual water flows. Figure 7 (a and b) provide the same results in thousand acre-feet (KAF), the unit used by water management agencies throughout the US west.

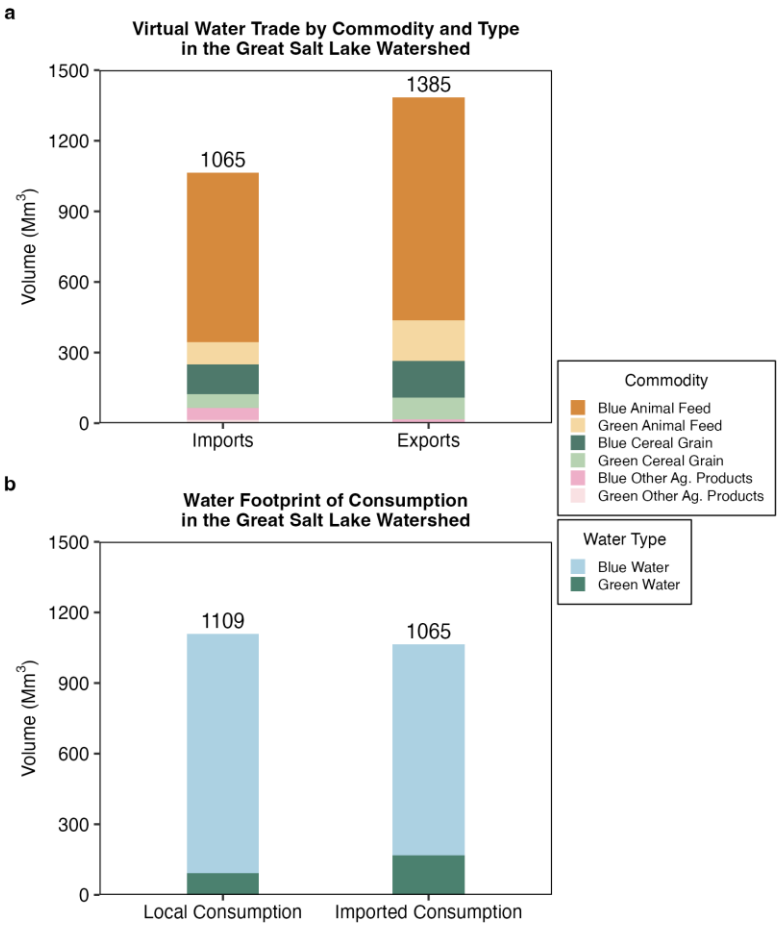


Figure 3. a) Mean annual virtual water imports to and exports from the Great Salt Lake watershed, 2010–2019 by agricultural sector and blue and green water components. b) Components of the water footprint of the Great Salt Lake watershed population disaggregated by local vs imported and blue vs. green water.

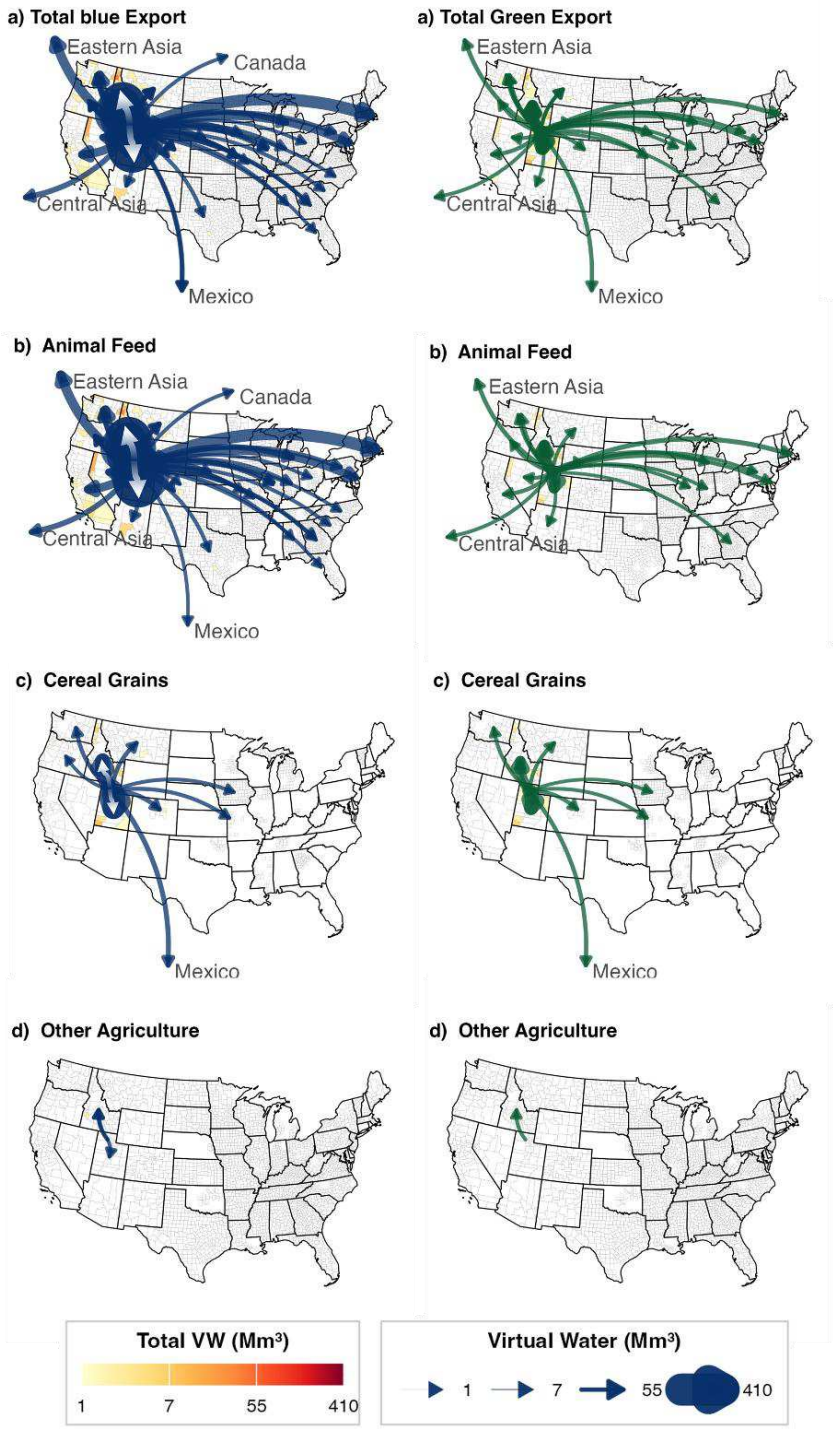


Figure 4. Domestic and international destinations of virtual water exports from the Great Salt Lake watershed. Data are disaggregated by Freight Analysis Framework commodity group and by blue and green water.

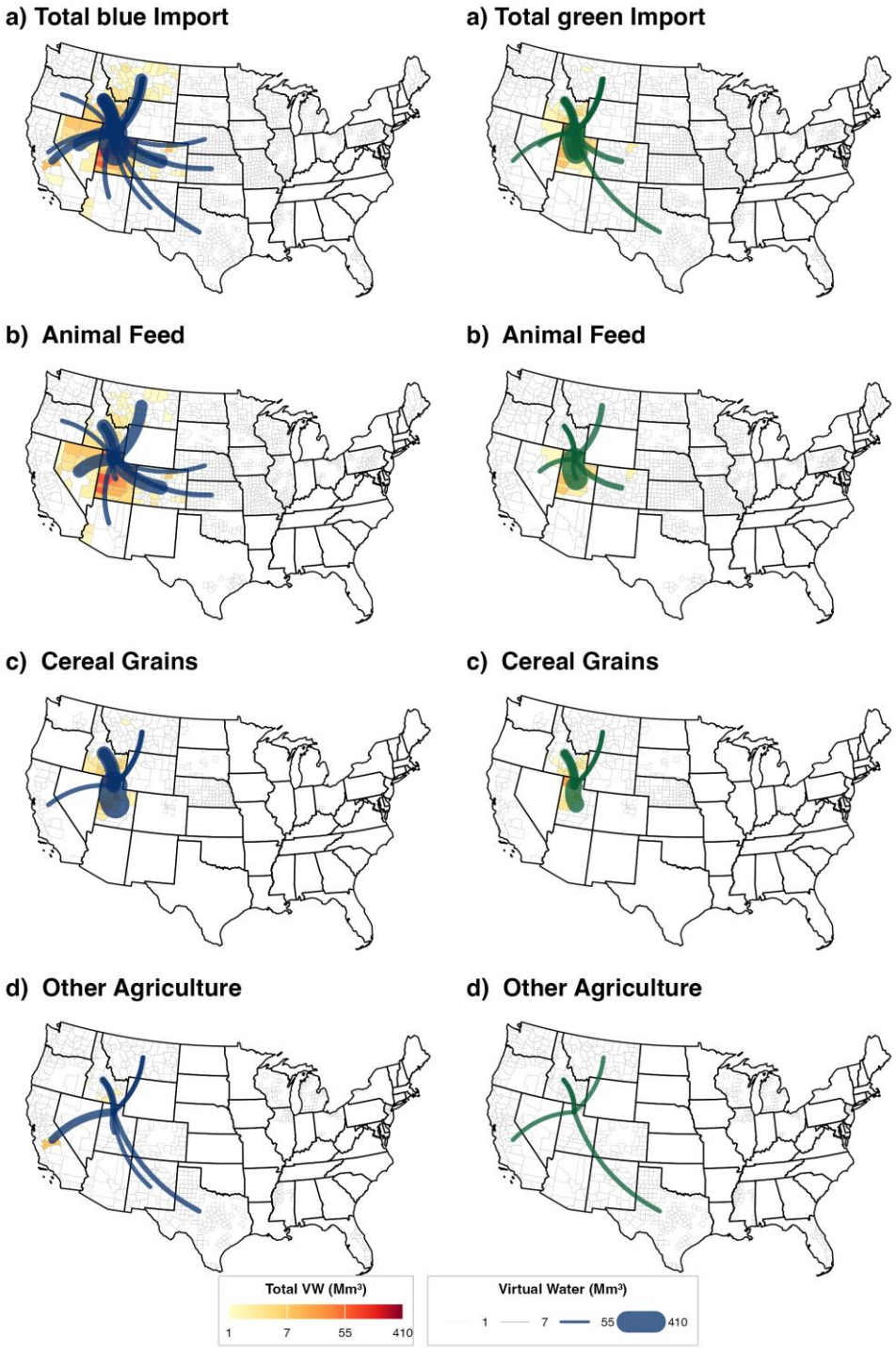
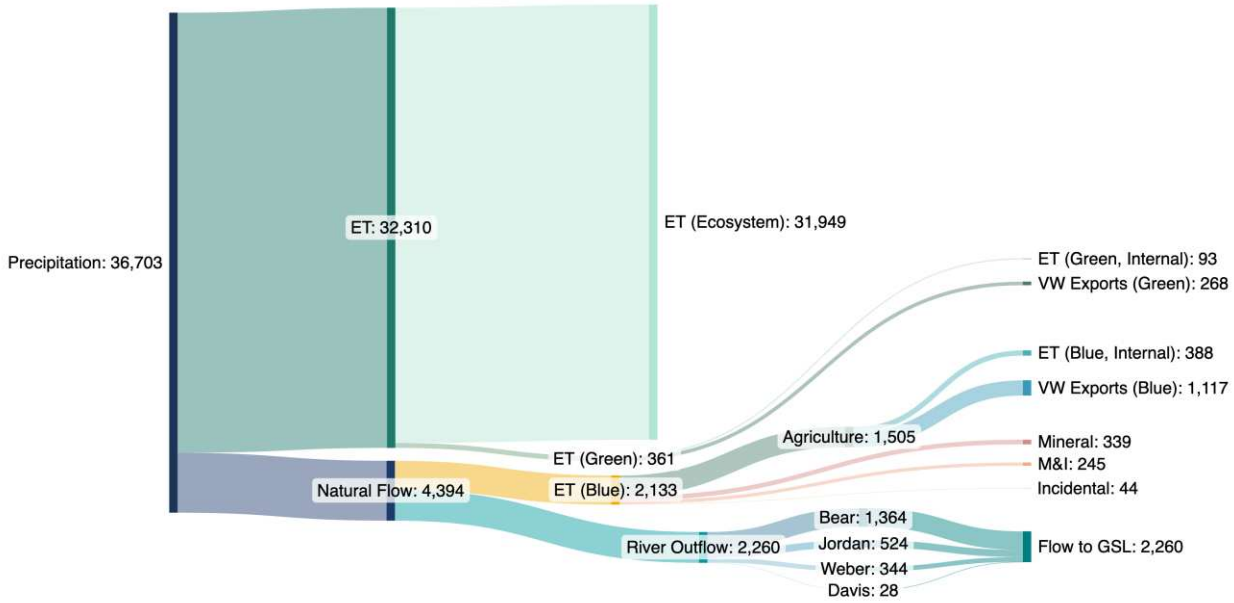


Figure 5. Domestic and international origins of virtual water imports to the Great Salt Lake watershed. Data are disaggregated by Freight Analysis Framework commodity group and by blue and green water.



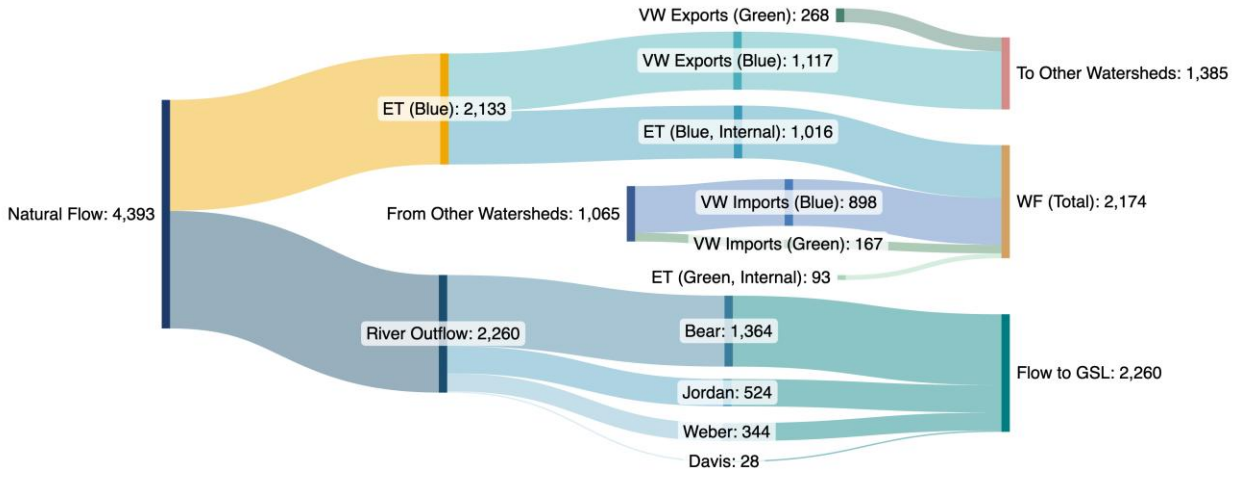
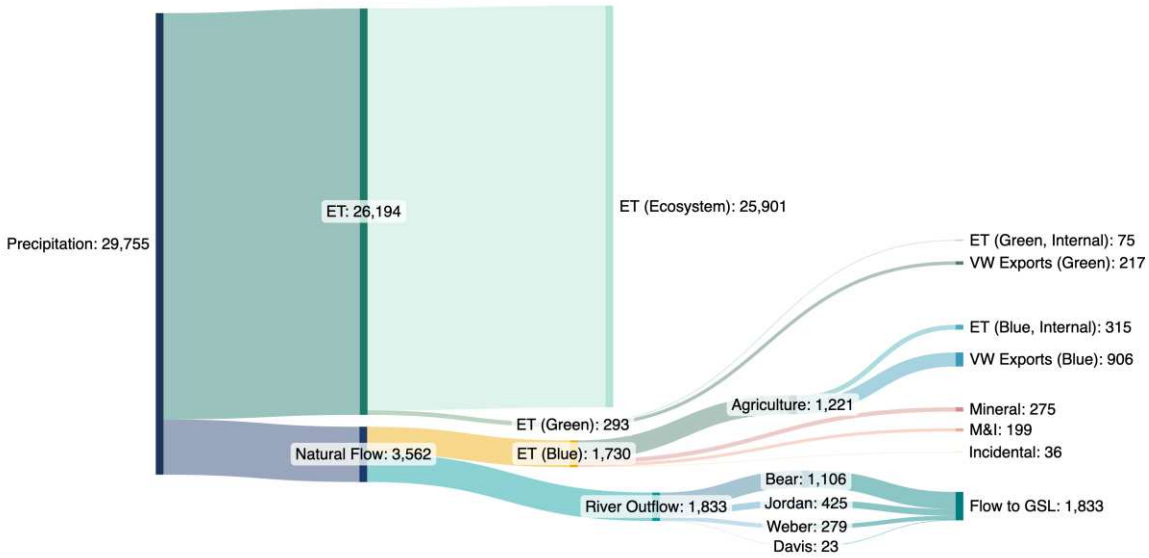
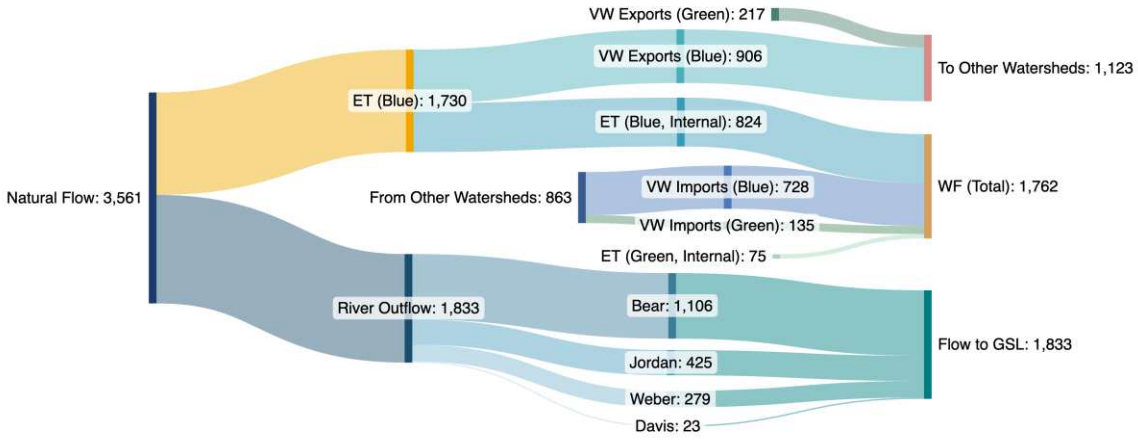


Figure 6. a) Integrated WBF model results for the GSL watershed and b) Management-relevant components. Units are Mm^3yr^{-1} 2010–2019 means.



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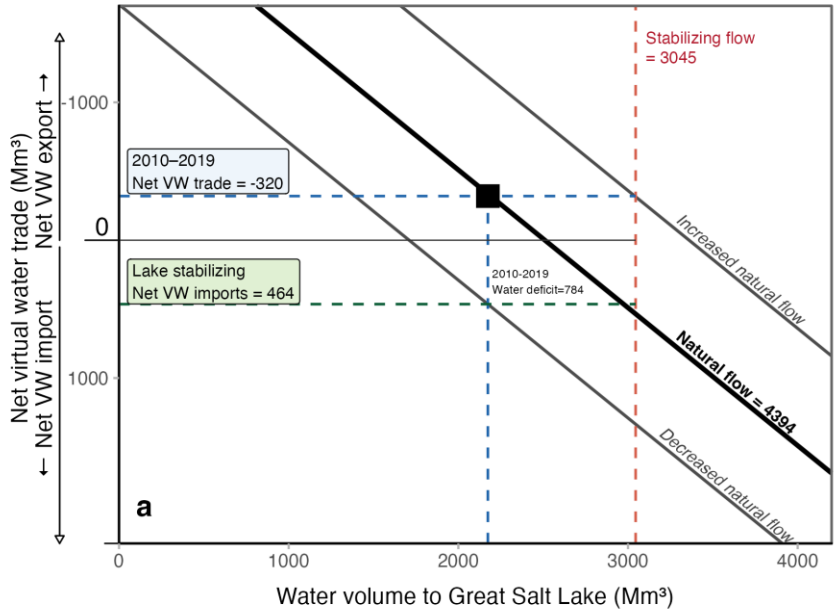
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278 Management-relevant components. Units in thousand acre-feet (KAF) 2010–
279 2019 means.

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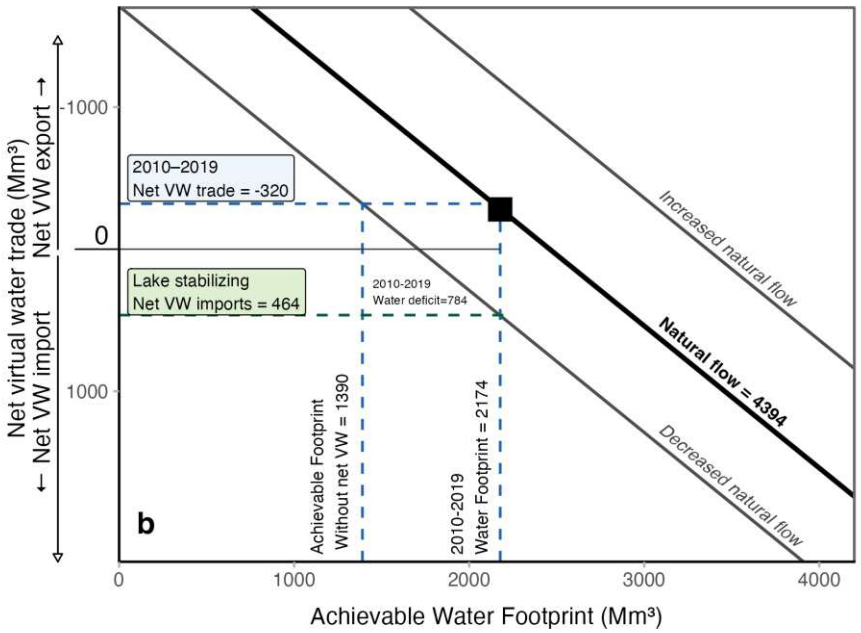
Trade-off Analysis

Trade-offs in water allocation occur among four variables: natural flow, water footprint, net virtual water trade, and flows to Great Salt Lake. A flow of 3045 Mm^3yr^{-1} was determined as required to stabilize Great Salt Lake at 1279.5 m by 2050 [21]. Figure 8a quantifies the trade-off between net virtual water trade and flows to Great Salt Lake with a linear function, resembling a Pareto front. If the water footprint of the population is held constant at the 2010–2019 mean of 2174 Mm^3yr^{-1}, the net virtual water trade of -320 Mm^3yr^{-1} results in a mean flow to Great Salt Lake of 2260 Mm^3yr^{-1}, a structural deficit of 784 Mm^3yr^{-1}. Consumption (ET_{blue}) could be reduced by either replacing local blue water consumption with virtual water imports or limiting blue virtual water exports to stabilize the lake with net virtual water imports of 454 Mm^3yr^{-1}. If climatic shifts increase natural flow, less virtual water imports are required. Ongoing climatic trends that are reducing natural flow [29] would increase the required level of net virtual water imports correspondingly (see narrow diagonal trade-off lines in Figure 8a).

Figure 8b quantifies the trade-off between net virtual water trade and the achievable water footprint while holding flow to Great Salt Lake constant at the stabilizing flow of 3045 Mm^3yr^{-1}, again showing that net virtual water imports of 454 Mm^3/yr^{-1} are needed to fully satisfy the current water footprint volume and restore Great Salt Lake. Increases in water footprint will result in decreased flows to Great Salt Lake unless compensated by greater net virtual water imports. Climatic trends in natural flow similarly change the virtual water imports required. Other scenarios could be devised within these trade-off spaces. The linear trade-off functions clearly illustrate how shifting from a net virtual water exporting watershed to a net virtual water importing watershed eases difficult trade-offs and reduces competition for water.



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311 **Figure 8**. (a) Linear trade-off between net virtual water trade and water volume to
312 Great Salt Lake while holding annual water footprint stable at the 2010–2019
313 mean of 2174 Mm^3. (b) Linear trade-off among net virtual water trade and the
314 achievable water footprint of the population, holding constant a stabilizing flow to
315 Great Salt Lake of 3045 Mm^3yr^{-1}. Natural flow variability is shown as narrow lines
316 around mean natural flow.

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Discussion

The application of the Watershed Balance and Footprint (WBF) model to the Great Salt Lake Watershed demonstrates its utility in identifying options for satisfying the water footprint of the resident population over time in a manner that softens trade-offs to environmental water needs, building on Pareto optimal tradeoffs research for environmental water management [30]. In this case, Great Salt Lake can be stabilized by reducing the water footprint—a difficult task in the face of rapid population growth—by increasing blue or green virtual water imports or by reducing blue virtual water exports. Without using the term, blue virtual water exports have become a political issue in the US West. In effect, this would make changes in the economic geography of agricultural production a crucial factor in avoiding water bankruptcy; this presents a challenge to traditional approaches to water governance.

Emphasizing virtual water imports could deliberately displace the water footprint of the population of the Great Salt Lake watershed to watersheds where trade-offs are less dire. For example, while virtual water imports from the neighboring Colorado River watershed would simply shift, rather than resolve, emerging issues of water bankruptcy, there are other options to import green virtual water that avoid 'water grabbing' [17].

Replacing blue with green water embedded in bulk industrial (e.g., fuel ethanol [31], lumber [32]) and, especially, bulk agricultural commodities through virtual water trade is a powerful means to readjust water demands in stressed and bankrupt watersheds. This is especially the case where expanded virtual water sources are varied, politically amiable, and have an economic interest in acquiring new agricultural markets. For example, the Mississippi River watershed exports 200 km^3yr^{-1} of green virtual water [33] and meets these criteria [12].

The WBF model presented here is applicable and valuable in varied watersheds. Small urban watersheds, for example, rely on extensive virtual water imports or inter-basin transfers. Many rural agricultural watersheds and commercial forestry regions that have low resident water footprints relative to natural flow can thrive as virtual water exporters, especially of green water. However, virtual water exports can have salient land use issues appurtenant to biomass commodity production. Each watershed has a different signature that can be quantified to assess water balances and strategic opportunities, as shown in Figure 1.

The WBF model also faces limitations. For example, in the Great Salt Lake watershed case, reforms, such as large-scale water leasing from farmers [34], would be required to initiate shifts in net virtual water trade. Further, water footprint and virtual water trade data are inherently less accurate and of courser temporal and spatial resolution than hydrologic data [8], potentially creating a data-based model limitation. Nonetheless, addressing watershed-scale water bankruptcy requires new approaches with models that illuminate the essence of the dilemma—which lies in water demands that are unsustainable with local water resources [1]. If the approach presented here in the form of the Watershed Balance and Footprint model aids in identifying feasible alternatives for effective

action, improvements in data needed to apply the model to specific watersheds are likely to follow.

Methods

Determining Watershed Area

Within the USGS Hydrologic Unit Code (HUC) system, the GSL Watershed includes Subregions 1601 (Bear) and 1602 (Great Salt Lake), spanning portions of Utah, Idaho, and Wyoming (see Figure 2a). Additional inter-basin transfers through the Central Utah Project (CUP) are delivered via the Municipal & Industrial System of the Bonneville Unit through the Jordan River [35].

Precipitation, Depletion and River Flow

Precipitation data for 2020–2024 were sourced from [36]. Using R [37]; annual precipitation records were extracted for the Bear River, West Desert, Jordan River, Weber River, and Utah Lake watersheds, corresponding to the watershed boundary. Natural system (non-agricultural ET) is 90.1% of precipitation [38]. Depletion data (ET_{blue}) from [36] were aggregated annually by sector (agricultural, incidental, municipal and industrial (M&I), and mineral) and scaled to the watershed. Annual Great Salt Lake influx data for 2000–2024 were sourced from "Streamflow Entering the Great Salt Lake," part of the larger "Collection of Great Salt Lake Data" accessed via HydroShare [39].

Local Water Consumption

Local blue water consumption ($ET_{blue,intenal}$) was calculated by subtracting blue virtual water exports from depletion totals. We estimated $ET_{green,internal}$ as 93 Mm^3 yr^{-1} by assuming that the same proportion of local consumption (48%) vs virtual water exports (52%) applies to green as to blue water. Crops embody both blue (from irrigation) and green (from precipitation) components.

Virtual Water Trade

Virtual water flow data were obtained from FEWSION Database™ [40]. The FEWSION Database™ estimates virtual water flows using USGS water withdrawal data [41], USGS sector-level water consumption coefficient estimates [42], commodity flow data [43], and US Census International Trade Data [44], among other datasets. Aspects of the commodity flow downscaling and virtual water flow estimation process have been published previously in [45–47] with [48] providing a comprehensive documentation.

Per these studies, commodity flow data were first downscaled from freight analysis zones [43] to the county-level using sector-level indicators of economic activity, concentration, and demand to match the geographic resolution of USGS water withdrawal data. After downscaling commodity flows, the resulting networks were normalized by mass and multiplied by water withdrawal and consumption data to estimate virtual water outflows. International export downscaling was conducted using US Census state, commodity, and country

foreign trade data. Virtual water export data were then extracted for Great Salt Lake watershed counties for all commodities; however, only agricultural commodities were used in this study as they constitute the vast majority of virtual water trade.

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