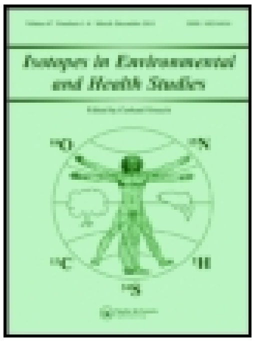

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Urban water – a new frontier in isotope hydrology†

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ABSTRACT

Isotope hydrology has focused largely on landscapes away from densely inhabited regions. In coming decades, it will become increasingly more important to focus on water supplies and dynamics within urban systems. Stable isotope analyses provide important information to water managers within large cities, particularly in arid regions where evaporative histories of water sources, vulnerabilities, and reliabilities of the water supplies can be major issues. Here the spatial and vertical understanding of water supporting urban systems that comes from stable isotope analyses can serve as a useful management tool. We explore this research frontier using the coupled natural–human landscape of the Salt Lake Valley, USA, with its greater than one million inhabitants. We first provide data on the stable isotope ratios of the hydrologic system's primary components: precipitation, incoming surface waters, and terminus waters in this closed basin. We then explore the spatial and temporal patterns of drinking waters within the urban landscape and the new opportunities to better link isotope ratio data with short- and long-term management interests of water managers.

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Hydrogen-2; isotope hydrology; oxygen-18; tap water; Salt Lake Valley; urban water isotopes

1. Introduction

The quality and reliability of water supplies to support human development and cities in arid regions of the world is of paramount interest. With growing demands for water in arid regions and the challenges of supplying that water in the face of climate changes, it is increasingly important to understand details of our water supplies [1–3]. While water managers have historically focused on providing a constant water supply to urban consumers, there is often less focus on the true origins and evaporative histories of these culinary waters. For many water utilities, there is a lack of information regarding the vulnerabilities of today's water supplies with the prospects of climate change impacts [2,4]. Here a spatial and vertical understanding of the isotopes in water supplying urban systems, including the reuse of processed water within urban watersheds, can serve as a management tool by providing information on the origins and evaporative histories of urban water supplies [3,5,6].

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Water is an essential resource for human development and sustainability, and is limited in arid regions. Historically in the driest regions of the western USA, it was common to find populations settling and communities developing closest to reliable montane or riverine water sources. However, over the past century, the development of long-distance water conveyances has altered this settlement pattern in some places, allowing megapolitan regions, such as Los Angeles and Phoenix, to develop independently from the initial sources of their water supplies [7]. In the arid state of Utah (USA), long-distance transport of water into the region was not historically required, although trans-basin water exchanges take place today [8] and continue to be developed. As a consequence, we find nearly 90 % of the state's 3 million residents clustered in a few valleys immediately adjacent to the Wasatch and Uinta Mountains of northern Utah. In the most populous of these valleys, the Salt Lake Valley (SLV), more than one million individuals depend on adjacent mountain snowmelt waters as their primary water resource for culinary, industrial, and agricultural needs [2]. To a lesser degree, both agriculture and communities within the SLV also utilise groundwater that has been recharged by these same montane systems [9–11].

Maps of the isotope ratios of water supplies reflect the complex use of groundwater, regional surface sources, and trans-basin water transfers [12]. In some urban landscapes, recycled waters (i.e. grey water, groundwater recharging with transported water, etc.) add further complexity to the urban water isoscape. The inclusion of water isotopes into the ecohydrology of urban systems and of coupled montane–urban landscapes is an exciting frontier where our fundamental science can be applied to immediate social and economic benefit. We explore this frontier in the SLV, an urban region in an arid landscape of the western USA. Here, as in many developing urban regions away from coastal regions or major river ways, water is transported across a coupled natural–human landscape, from its montane source to regions of human activity. Within the SLV, a rapidly growing population depends on these transported surface waters from the adjacent Wasatch Mountains (intra-basin) and Uinta Mountains (inter-basin) as their primary water resource for culinary and industrial needs.

2. Methods

The SLV lies within the Great Basin, an extensive interior basin of western North America where stream inputs flow into one of several closed basins. This situation provides an unique opportunity to describe a more complete isotope hydrologic cycle, capturing inputs and outputs as well as the consequences of changes in both environmental and population drivers influencing hydrological components. For the SLV, precipitation falling in the Wasatch Mountains terminates in the Great Salt Lake, resulting in a flow path of less than 200 km.

Over the past three decades, we have collected incoming precipitation, surface waters, tap waters, atmospheric waters, and terminus waters for this coupled natural–human hydrologic system. We have sampled (a) precipitation, (b) surface stream and river waters entering into the SLV, (c) tap waters (drinking water) within the SLV, and (d) the Great Salt Lake. Water samples were collected and stored in glass vials sealed with hand-tightened, lined caps. Precipitation samples were collected from rain gauges located at private residences on the east side of the SLV (lat. 40.667, long. −111.799, 1562 m and lat. 40.783, long. −111.846, 1582 m) at approximately 8 a.m. following the day of the precipitation event. Tap waters were collected from private residences, public buildings, and commercial buildings across the SLV. Long-term observations are presented for tap waters from the Skaggs Biology Building on the University of Utah (lat. 40.763, long. −111.8485, 1426 m) and the first of the private residences above. Surface waters were also sampled on four of the major streams entering the SLV (Big Cottonwood Creek, Little Cottonwood Creek, Mill Creek, and Red Butte Creek). As these streams eventually feed into the Jordan River as it passes through the SLV, Jordan River water was sampled near the entry into urban regions (10600 South, lat. 40.7259, long. −111.9261, 1291 m) and near the northern extent of the river (2100 South, lat. 40.5592, long. −111.9081, 1315 m). Parafilm was used to seal the cap-vial interface on all vials to reduce the probability that the cap loosened during transport or storage. Once collected, water samples were stored in a refrigerator until analysis.

The data presented here are part of long-term hydro-isotopic observations within a coupled natural–human landscape, providing a data foundation for future interpretations of both climate- and management-based changes in isotope hydrology. Since July 1988, over 7750 observations have been made from a total of 126 different locations across the SLV, with 34 of these locations having been sampled > 15 times (Figure 1). Since 2004, 14 of the SLV locations and one Great Salt Lake location have been monitored on a bi-weekly to monthly basis.

All water samples have been analysed for stable isotope ratio at the Stable Isotope Ratio Facility for Environmental Research (SIRFER) at the University of Utah (http://sirfer.utah.edu). Over three decades, SIRFER has progressed through multiple approaches to

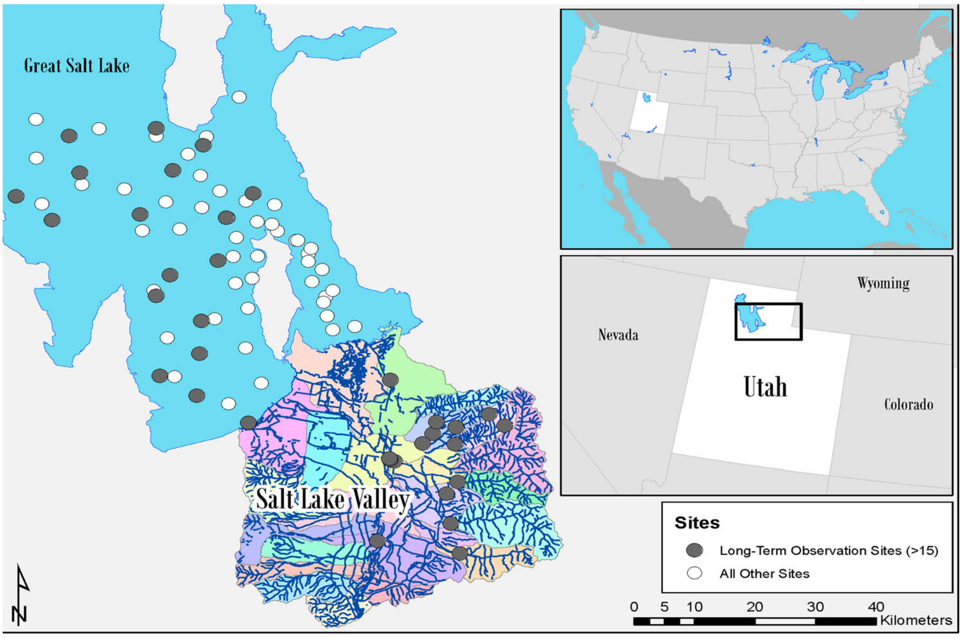

Figure 1. Map of the Great Salt Lake and the natural and urbanised landscape of SLV and Wasatch Mountains where waters in this study have been collected for δ^{2}H and δ^{18}O analyses.

measure the δ^2H and δ^{18}O values of water. For δ^2H analyses using Isotope Ratio Mass Spectrometer (IRMS) analytical instrumentation, these have included zinc reduction [13] and pyrolysis [14] preparation approaches. For δ^{18}O analyses using IRMS analytical instrumentation, these have included CO_2/H_2O equilibration [15] and pyrolysis [14] preparation approaches. Over the last four years, all water samples have been analysed using a Picarro cavity ring-down spectrometer [16]. Data are expressed using δ notation. In tying into the V-SMOW scale, we use a 2-end-member correction with laboratory reference materials that have been calibrated against International Atomic Energy Agency (IAEA) reference standards. Each analytical run included blind samples of Quality assurance/Quality control (QA/QC) water reference materials, long-term analytical precisions (SD) of 1.56 ‰ and 0.21 ‰ for δ^2H and δ^{18}O analyses, respectively.

3. Results and discussion

Observations of precipitation over a 16-year period revealed a common meteoric water line at two sampling locations on the east side of SLV. Therefore, the two data sets were combined to produce a single local meteoric water line (Figure 2). The local meteoric water line, $\delta^2H = 7.87\ \delta^{18}O + 7$, is statistically significant ($n = 726$, $r^2 = 0.966$, $p < .001$) and similar to the observed global meteoric water line (Figure 2). In calculating the local meteoric water line, 74 summertime precipitation values greater than $\delta^{18}O > 7$ ‰ were not included in the regression calculations ($n = 74$), because these precipitation values fell below the local meteoric water line with a slope of 4.7, consistent with an appreciable sub-cloud partial evaporation of falling raindrops. Local meteoric water lines have been reported in the region, and the relationships observed in this study are similar to those observed for Idaho Falls, Idaho [17] and selected sites across southeastern Idaho, western Wyoming, and south-central Montana [18].

The stable isotope ratios of surface waters undergo significant changes as water flows through the SLV (Figure 3). The Jordan River, an 83-km river, conveys water northward from Utah Lake through the populated SLV and terminates in the Great Salt Lake. As

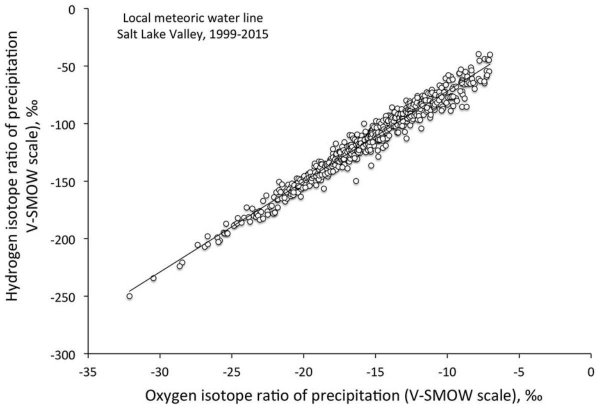

Figure 2. The meteoric water line for precipitation in the SLV based on sampling locations on the eastern edge of the valley and sampled between 1999–2015 ($n = 726$). The local MWL is $\delta^2H = 7.87\ \delta^{18}O + 7$.

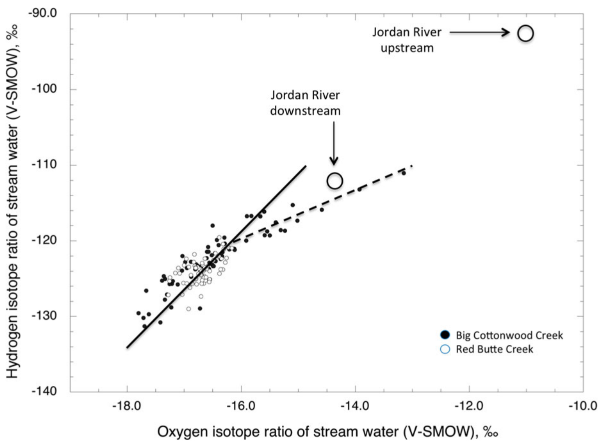

Figure 3. Long-term average δ^{2}H and δ^{18}O values of tap water sources (montane streams), tap waters, Jordan River, and the Great Salt Lake (basin terminus). Data are from Table 1. Only stream waters and tap waters come close to falling along the local meteoric water line.

the Jordan River enters the SLV, the average stable isotope ratios were δ^{2}H = −92.1 ± 8.9 ‰ and δ^{18}O = −10.7 ± 1.6 ‰ (n = 142). Over an 11-year period, these river samples were always evaporatively enriched from the local meteoric water line (Figure 2) as expected, since the Jordan River is fed by evaporatively enriched waters from Utah Lake, a shallow lake whose water have an opportunity to evaporate in the low humidity environment that characterises Utah. As the Jordan River flows northward through the SLV, water is added from montane streams, sheet flow, urban runoff, sewage treatment facilities, and groundwater sources that may or may not have interacted with the urban environment. While most streams (e.g. Red Butte Creek) entering the SLV have waters isotopically similar to the local meteoric water line, Big Cottonwood Creek has a reservoir in its upper reach that releases isotopically enriched water during summer months even

Table 1. Average hydrogen and oxygen isotope ratios of stream waters from the Wasatch Mountains entering into the SLV and emptying into the Jordan River, tap waters from three regions within the SLV, the Jordan River as it passes through the urban environment, and the Great Salt Lake (terminus of this hydrologic basin).

	n	δ^{2}H (‰)	δ^{18}O (‰)
Incoming streams			
Big Cottonwood Creek	77	−122.4 ± 4.0	−16.5 ± 0.8
Emigration Creek	82	−124.3 ± 3.0	−16.7 ± 0.5
Little Cottonwood Creek	67	−121.6 ± 4.2	−16.5 ± 0.8
Mill Creek	133	−126.3 ± 2.2	−17.0 ± 0.5
Red Butte Creek	352	−123.2 ± 3.5	−16.3 ± 0.5
Drinking waters			
University tap water	127	−120.3 ± 3.3	−15.8 ± 0.8
Holladay tap water	20	−123.3 ± 2.2	−16.5 ± 0.5
Salt Lake City tap water	5	−124.7 ± 1.2	−16.9 ± 0.2
Jordan River			
2780 South	142	−107.2 ± 8.8	−13.6. ± 1.6
10600 South	42	−92.1 ± 8.9	−10.7 ± 1.6
Terminus			
Great Salt Lake	409	−63.7 ± 11.1	−4.5 ± 2.1

though the annual average is not different among incoming streams (Table 1, Figure 3). Just before the Jordan River exits the SLV and enters into the Great Salt Lake, the average stable isotope ratios of river water have become more depleted than their initial values: $\delta^2H = -107.2 \pm 8.8$ ‰ and $\delta^{18}O = -13.6 \pm 1.6$ ‰ ($n = 142$). What factors have contributed to the isotopic depletion of waters in the Jordan River?

One of the factors contributing to the decreases in the isotope ratios of waters in the Jordan River is input from montane streams. The stable isotope ratios of montane surface waters entering the SLV shared common values (Table 1), despite differences in the extent and elevation differences of these watersheds. If incoming stream waters were the only input into the Jordan River as it moves through the SLV, then, using a 2-end-member mixing model, we can calculate the expected proportions of montane stream water inputs required to achieve stable isotope mass balance of the Jordan River at its northern end. Given the isotope ratios of the montane streams and the changes in the isotope ratios of the Jordan River, we calculated with both ^2H or ^{18}O observations that 48% of the Jordan River at its northern terminus would have been derived from montane streams (assuming that as the only river water input) and 52% would have been derived from Utah Lake as the water entered the SLV. However, a river's water balance is more complex, with local precipitation, groundwater, sewage treatment water, and transported water also influencing flow rates and isotope values.

Limited efforts have attempted to address the challenge of quantifying the water balance of waterways in arid regions as these rivers pass through a complex urban environment with its many inputs and losses affecting flow rates. Yet the need for such information is critical in arid regions, where municipalities and other entities vie for this limited resource and future demand and climate change will alter the availability of water resources. Although the isotope mass balance calculations above predict that 48% of the water within the lower reaches of the Jordan River is outflow from Utah Lake, a recent study estimated that 53% of the river flow originated from Utah Lake inputs, while only 47% was attributed to groundwater, streams, sewage effluent, stormwater, irrigation water, and unknown sources within the reach of the Jordan River described above [19,20]. Given limited direct flow measurements essential to mass balance approaches, a 5% difference in river water inputs (48 versus 53%) has implications for water managers pumping groundwaters at various locations within the SLV and agencies attempting to improve the quality of water in urban environments. While a 5% difference in estimates might seem rather small, translating this number into an absolute amount of water approaches the volumes utilised by smaller water districts within the SLV. To achieve full isotope mass balance in the lower reaches of the Jordan River assuming that 53% of the river water derived from Utah Lake requires a third water source with stable isotope ratios values more negative than has been seen in stream discharges (Table 1). Shallow groundwater stable isotope ratios cannot be that source, since they tend to be more positive than seen within streams (δ^2H values varied from −118 to −92 ‰ and $\delta^{18}O$ values from −16.3 to −10.9 ‰) [21]. Thus, while shallow groundwater observations can be useful in constraining mass balance interpretations of fluxes into and out of the river, in this case they are unlikely to be a source contributing to river isotope mass balance if 53% of the river flow originated from Utah Lake inputs. Instead, observed shallow groundwater δ^2H and $\delta^{18}O$ values suggest possible groundwater recharge from the Jordan River into lower portions of the SLV and montane inputs as groundwater inputs at higher elevations nearer to the base of the Wasatch Mountains. It is more likely that the estimated 53% of water in the Jordan River water at its northern end as having been transported in from Utah Lake [19,20] is too high. This percentage does not allow for an isotopic mass balance using observed water isotope values. This challenge speaks to the benefits of isotope hydrologists working with water managers in urban systems using isotope observations to better constrain isotope/flux dynamics so that a dynamic urban water balance can be more completely described.

Over the past five years, precipitation inputs have been below average with much of the precipitation falling as rain at lower elevations. In managing to provide a reliable culinary water supply, water managers frequently adjust water supplies and switch among water sources. Impounded culinary reserves can become evaporatively enriched as is implied with summertime flows in the Big Cottonwood Creek where a fraction of the summertime water is derived from an upstream reservoir (dashed line in Figure 3). Over the last two years, tap water isotope values have gradually increased with smaller snowpacks and warmer temperatures (Figure 4). While the exact source(s) of the culinary water supplies delivered to this residence as well as others in the neighbourhood are unknown, the water supplies are provided by a single water district (Salt Lake City Public Utilities). Much of the water district's culinary water is derived from streams emerging from the nearby Wasatch Mountains, including the Big Cottonwood Creek. Throughout much of the year, this culinary water source is evaporatively enriched, falling of the local meteoric water line ($\delta^2H = 4.7\ \delta^{18}O - 45$).

Isoscapes or maps of stable isotope ratio variations can be used to describe spatial distributions of tap water across the SLV [5]. When many tap waters are analysed instead of only a single location, it becomes clear that tap water sources consumed within an urban landscape exhibit strong spatial patterns, reflecting multiple isotopically distinct inputs (groundwater, locally derived montane waters, and inter-basin water transfers) [3,22,23]. Within the urbanised area of the SLV, isotope ratios of tap water show a wide range of variation and strong spatial patterning consistent with water district boundaries (Figure 5). Major features in the tap water isotope distribution do not follow hydrological or climatic

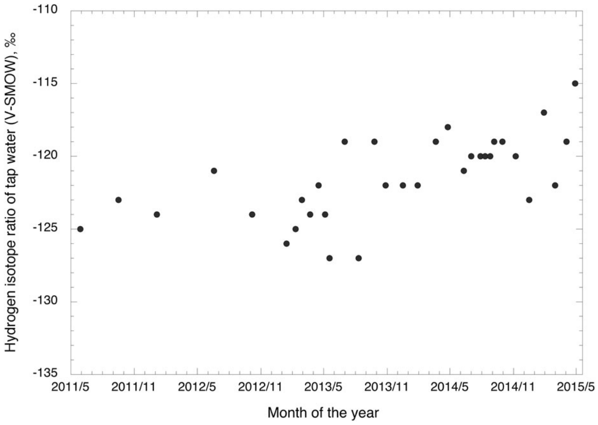

Figure 4. Hydrogen isotope ratios of tap water collected from two locations (a private residence in Holladay and a university building in Salt Lake City) between 2010 and 2015.

gradients, but are largely structured by boundaries between water management districts. Relationships between δ^{2}H and δ^{18}O values suggest that the majority of the tap water used in the SLV is derived from sources with a limited range of δ^{2}H and δ^{18}O values, but tap waters in specific water districts have experienced highly variable amounts of evaporation prior to its consumption. The tap water isotope ratios in all but one of the water districts have increased over the last several years (Jameel et al., personal communication), consistent with the time series trends for the two locations shown in Figure 4. The water isotope data for the single residence (Figure 4) and multiple districts across the SLV (Figure 5) are consistent with overall increases in evaporation of tap water consumed within the valley. Whether the isotopically enriched tap waters of recent times are associated with elevated temperatures and/or drought is not constrained at the moment, but certainly has ramifications for water supply management.

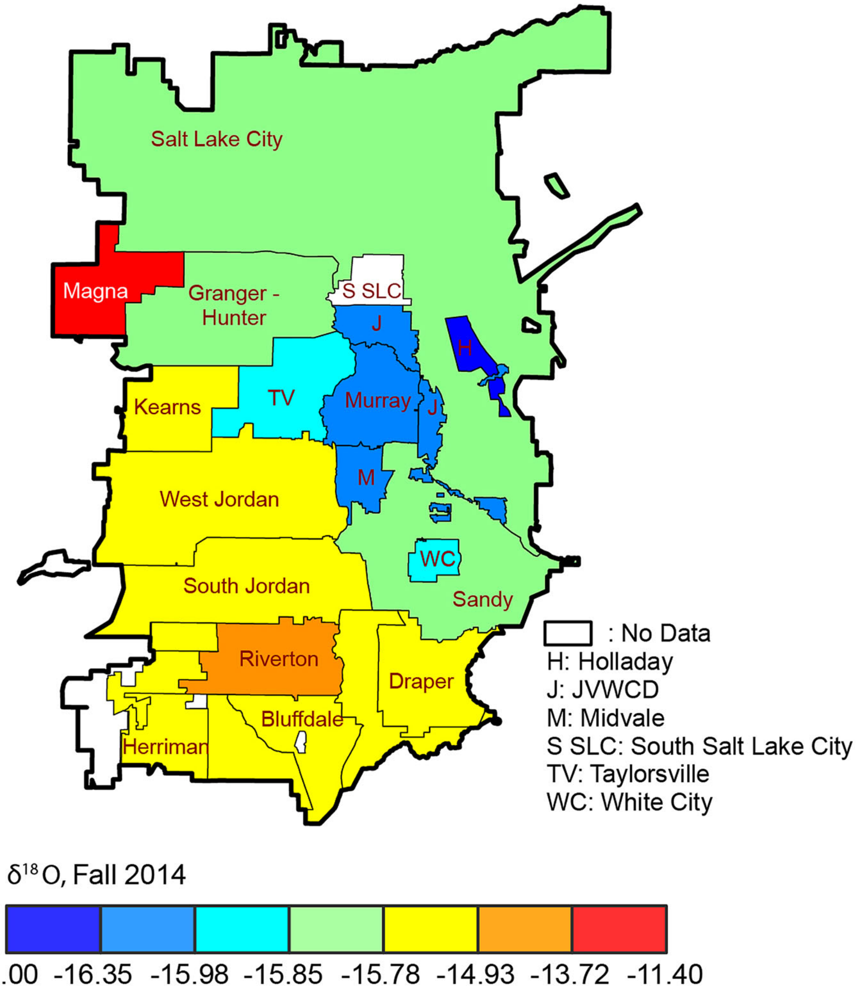

Figure 5. Plot of the average δ^{18}O values for tap waters collected in different water districts across the SLV, Utah, USA, in autumn 2014 from different locations across the SLV. Data are average of multiple locations, grouped by known water management district boundaries. JVWCD = Jordan Valley Water Conservation District.

4. Conclusions

The history of ecohydrology is often to focus on undisturbed watersheds away from highly inhabited regions. As one new frontier for our discipline, we propose that isotope hydrologists more fully embrace the opportunities that integrate water transport into and water consumption in urban landscapes. In this example of the SLV, we have highlighted several examples of current opportunities. We first provide data on the stable isotope ratios of the hydrologic system's primary components: precipitation, surface waters, tap waters, atmospheric waters, and terminus waters. We then explore the spatial and temporal patterns of water within the urban landscape and the new opportunities to better link isotope ratio data with short- and long-term management interests of water managers. We present an overview of the annual and inter-annual stable isotope ratio dynamics of these natural and urban waters and of the changes in isotopic composition that occurred spatially and temporally as water moved through a coupled natural–human system.

Stable isotope observations of water sources inputs, surface water hydrology, and drinking waters in a coupled natural–human urban landscape provide insights into the dynamics of potential human impacts on the hydrological cycle as water moves through an urban system. Our long-term and continuous monitoring of water isotopes within the SLV form the basis of interpreting long-term trends in human impacts on this regional water cycle.

Disclosure statement

No potential conflict of interest was reported by the authors.

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