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Special Section:
Socio-hydrology: Spatial and Temporal Dynamics of Coupled Human-Water Systems

Key Points:
- Municipal outdoor water conservation generates cross-scale interactions between the watershed and submunicipal processes
- Effects of outdoor water conservation on urban vegetation follow a socioeconomic gradient, with affluence a major driver for water stress
- Sociohydrology must account for heterogeneity within the urban water cycle and open the "black box" of the city

Supporting Information:
- Supporting Information S1

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Sociohydrological Impacts of Water Conservation Under Anthropogenic Drought in Austin, TX (USA)

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Abstract Municipal water providers increasingly respond to drought by implementing outdoor water use restrictions to reduce urban water withdrawals and maintain water availability. However, restricting urban outdoor water use to support watershed-scale drought resilience may generate unanticipated cross-scale interactions, for example, by altering drought response and recovery in urban vegetation or urban streamflow. Despite this, urban water conservation is rarely conceptualized or modeled as endogenous to the water cycle. Here we investigate cross-scale interactions among urban water conservation and water availability, water use, and sociohydrological response in Austin, TX (USA) during a recent anthropogenic (human-influenced) drought. Multiscalar statistical analyses demonstrated that outdoor water conservation for reservoir management at the municipal scale produced responses that can cascade both "upward" from the city to the watershed (e.g., decoupling streamflow patterns upstream and downstream of Austin at the watershed scale) and "downward" to exert heterogeneous effects within the city (e.g., redistributing water along a socioeconomic gradient at submunicipal scales, with effects on terrestrial and aquatic ecosystems). We suggest that adapting to anthropogenic drought through irrigation curtailment requires sustained engagement between hydrology and social sciences to integrate socioeconomic status and political feedbacks within and among irrigator groups into the water cycle. Findings from this cross-disciplinary study highlight the importance of a multiscalar and spatially explicit perspectives in urban sociohydrology research to uncover how water conservation as adaptation to anthropogenic drought links hydrological processes with issues of socioeconomic inequality and spatiotemporal scale in the Anthropocene.

1. Introduction: Urban Systems Under Anthropogenic Drought

The frequency, severity, and environmental impacts of drought, defined broadly as "less water in the hydrological system than normal" (Van Loon et al., 2016, p. 362), are increasingly influenced by human activities. Human-influenced, or anthropogenic, drought arises through a complex interplay among biophysical and social processes including meteorological variability affected by global climate change, water storage and withdrawals for human use, and changes in land use/land cover that alter the water cycle (Van Loon et al., 2016). As drought becomes increasingly anthropogenic, there is an urgent need to understand how human societies, and specifically cities, influence drought occurrence, propagation, and recovery.

Urban water conservation programs have been identified as a potential tool to mitigate anthropogenic drought impacts, particularly in regards to outdoor water use in urban areas (Garcia et al., 2016; Kenney, 2014). Outdoor water use (e.g., for irrigating turfgrass) can represent a significant component of urban water withdrawals. For example, nearly 50% of August water withdrawals were attributed to outdoor use in Austin, TX (USA) prior to recent droughts (Gregg et al., 2007). Outdoor water use can vary widely over space and time as a result of complex interactions among weather and climate patterns, hydrology, land use, socioeconomic status, and other social factors (Breyer et al., 2012; Domene et al., 2005; Saurí, 2013). In U.S. cities, outdoor water use restrictions are estimated to reduce residential water consumption 18%–56% during drought (Gober & Quay, 2015; Mayer et al., 2015). Because of its linkages to climate and its capacity for rapid (subannual) curtailment, conservation of outdoor water use has been identified as a potential urban climate adaptation strategy (AghaKouchak et al., 2015; Hogue & Pincetl, 2015). However, the slow-moving (interdecadal) drivers out outdoor water use, such as land use patterns and cultural practices, render outdoor water use a vexing adaptation problem (Gober et al., 2016).

Outdoor water use restrictions may also generate unexpected biophysical feedbacks because urban water use is not a hydrological endpoint, but rather an entry point into the human-dominated urban water cycle. Following withdrawal, water is spatially redistributed along infrastructure networks, which may lead to changes in subsurface storage through pipe leakage (Bhaskar et al., 2015). In Austin, TX, for example, an estimated 8% of flow through city water mains becomes groundwater recharge, representing >5% of total annual recharge (Garcia-Fresca & Sharp, 2005; Passarello et al., 2012). Outdoor water use may be evapotranspired by urban vegetation, while water beyond vegetation requirements can recharge shallow groundwater systems as return flow (Christian et al., 2011). Because of these interactions, restrictions on outdoor water use may impact urban ecohydrological processes, especially during drought. For example, curtailing irrigation may affect the way urban vegetation both responds to and helps mitigate the urban heat island effect (Guhathakurta & Gober, 2010; Jenerette et al., 2016; Shiflett et al., 2017; Zipper et al., 2017a), or reduce groundwater recharge from return flows and contribute to decreased storage in shallow aquifers (Bhaskar et al., 2016). While the impacts of groundwater recharge on ecohydrological processes are complex and nonlinear (Booth et al., 2016), previous work has demonstrated that impacts of urbanization can propagate through groundwater flow systems to impact nonurban ecosystems (Zipper et al., 2017c) and groundwater discharge to streams is a key control over low flows (van Lanen & Wanders, 2012; Van Loon & Laaha, 2015). Given that previous research has estimated that up to 90% of baseflow in Austin may be derived from urban sources (Christian et al., 2011), reductions in urban irrigation may inadvertently increase the occurrence of hydrological drought in urban streams.

These complex interactions suggest a need to situate urban water conservation within a coupled multiscalar sociohydrological system, rather than framing it as a separate demand-side urban governance response. Yet historically, drought modeling has siloed off the demand-side processes shaping urban water use from the supply-side processes governing urban water availability, treating drought as an exogenous forcing imposed on both (Mishra & Singh, 2010). As the emergence of anthropogenic drought erodes the conceptual boundaries between biophysical and social systems, understanding urban water conservation as a cross-scalar sociohydrological drought response may become increasingly important to meeting future water sustainability challenges and avoiding maladaptive decision making (Blair & Buytaert, 2015; Garcia et al., 2016; Pande & Sivapalan, 2016). Such integrated understanding may also help reduce intersectoral water conflict over common water resources.

To enhance understanding of the effects of drought and sustained reductions in outdoor water use on urban sociohydrological processes across scales, this study asked, *how does urban water use affect and respond to watershed-scale drought, and what are the impacts of drought-induced urban water conservation measures on local ecosystems and the broader watershed?* To address this question, we performed integrated analyses of the interactions and feedbacks among Texas Colorado River discharge, water withdrawals for urban use, urban vegetation, urban streamflow, and meteorological drought severity in Austin, TX, a city that implemented unprecedented emergency conservation measures to curtail outdoor water use in response to recent anthropogenic drought. Broadly, we hypothesized that outdoor water use restrictions will alter interactions between sociohydrological processes occurring at watershed and municipal scales by attenuating the coupling between municipal water withdrawals and upstream/downstream watershed hydrology, while also compromising the ability of urban vegetation and streamflow to recover from drought. We divided the overarching research question into three testable hypotheses that are interrelated through the coupled regional-local water cycles, each associated with a statistical model at a different scale:

H1: Water conservation measures reduce urban water use, which, in turn, decouples the relationship between urban water withdrawal and upstream water availability at the city scale, while also decoupling the relationship between drought and downstream water flow at the watershed scale due to reduced return flows. We test this hypothesis using structural equation modeling (section 3.1).

H2: Within the City of Austin, water conservation alters the dynamics of urban vegetation, leading to decreasing “greenness” in vegetated land cover over time during periods of restricted irrigation. We test this hypothesis using hierarchical linear regression modeling (section 3.2).

H3: Within the City of Austin, water conservation has reduced subwatershed discharge by limiting contributions to baseflow from excess irrigation. We test this hypothesis using correlation analysis (section 3.3).

By synthesizing results regarding these hypotheses at different scales, we addressed our overarching research question through the lens of sociohydrology, an emerging field which treats humans and water as interdependent components within an explicitly coupled human-environmental system (Sivapalan et al., 2012, 2014). In particular, we highlighted how water conservation as a municipal-scale reservoir management strategy may trigger unanticipated cross-scale interactions, cascading "downward" from the watershed to affect subcity scale ecohydrological processes and "upward" from the city to the watershed by affecting linkages among climate and streamflow. Our findings on the coupled effects of outdoor water use suggest a need for multiscalar, spatially explicit sociohydrological analyses that "open the black box of the city" by linking fine-scale social and biophysical processes shaping how water flows within urban areas to coarser-scale processes upstream and downstream of the urban water withdrawal point.

2. Study Area: The Shifting Relationship Between the Texas Colorado River and Austin, TX

Our study area is Austin, TX (Figure 1), a rapidly growing city in the Texas Colorado River ("Colorado River" hereafter) basin, which is prone to cycles of extreme flooding and drought. Originating in New Mexico and

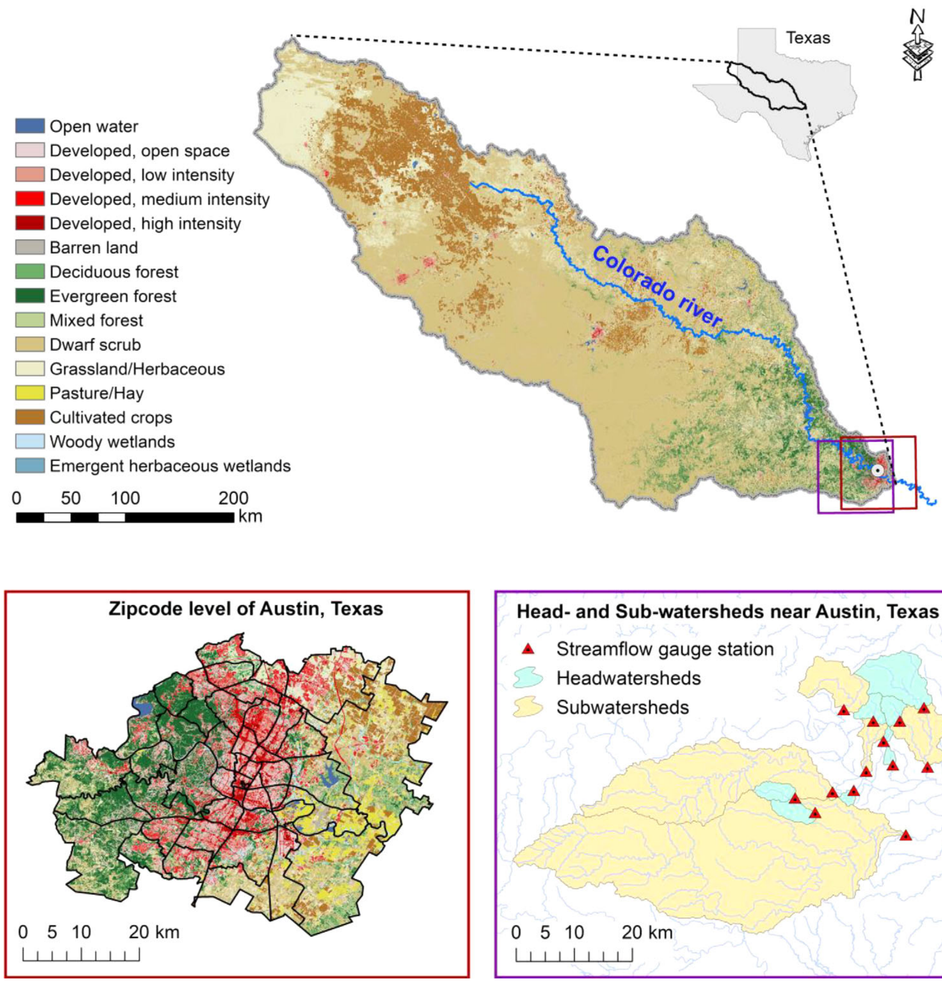

Figure 1. Study area. The Colorado River Basin upstream of the City of Austin, TX, along with insets of the municipality of Austin, forming an integrated urban-regional sociohydrological system.

west Texas, the Colorado River provides a surface water supply for upstream municipalities and downstream irrigators before discharging to Matagorda Bay along the Gulf of Mexico. Flow is regulated at the Highland Lakes, a series of six dams located northwest of Austin and managed by the Lower Colorado River Authority (LCRA). Within the Highland Lakes, Lakes Travis and Buchanan are Austin's municipal water supply reservoirs and serve as the primary water availability indicators used to allocate stored water among sectors, principally the City of Austin, Gulf Coast rice growers, and environmental flows.

Austin's relationship with the Colorado River has pivoted from accelerating water withdrawals (1930s–1980s) toward voluntary conservation (1990s–2008) and, more recently, mandatory irrigation curtailment (2009 to present). As such, Austin provides an ideal site to investigate outdoor water conservation through the lens of coupled sociohydrological systems.

2.1. 1930s–1980s: Increasing Urban Water Use and Shifting Urban/Rural Power Dynamics

The LCRA is a public conservation and reclamation authority created in 1934 to regulate Colorado River flow for urban flood control, downstream flood-irrigated rice cultivation, and hydroelectric power generation. Gulf Coast rice growers were originally key beneficiaries of LCRA infrastructure. However, the advent of hydroelectric power propelled rapid post-WWII economic development and urban population growth, shifting relative political power upstream, away from rice growers and toward urban users. Austin's postwar growth led to a vast expansion of low-density residential landscapes dominated by irrigated turfgrass (Karvonen, 2011). Increasing urban water withdrawals during this period created tension between Austin and downstream rice growers, culminating in a 1988 legal battle that cemented Austin's dominance through a "firm" water contract, guaranteeing reliable urban water supplies (Sanson, 2008). By contrast, rice growers received an "interruptible" contract that made agricultural releases contingent on reservoir storage; a subsequent 2010 plan made environmental flows to Matagorda Bay another "firm" water user with priority over rice growers (Lower Colorado River Authority, 2015).

2.2. 1990s–2008: Urban Water Demand Management and Voluntary Water Conservation

Austin's current population of nearly 900,000 has doubled since 1990, with over 400,000 more residents projected to arrive by 2040 (City of Austin, 2016). However, urban water withdrawals from Highland Lakes have increased more slowly than population since 1990 because Austin, like many US cities, shifted its water provisioning strategy toward managing urban water demand (DeOreo et al., 2016). Demand management produced a range of water conservation programs, including increasing block-rate pricing, conservation outreach campaigns, incentives for xeriscaping and rainwater harvesting, as well as rebates for water-efficient appliances. Between 1984 and 2004, water conservation in Austin reduced withdrawals by an estimated 22,000 m^3 (5.8×10^6 gal.) per day (Blue et al., 2015). However, because demand management primarily affected indoor water use, outdoor water use has increased as a share of residential consumption. Austin households were estimated to use 20,000 m^3 outdoors out of 64,000 m^3 total annual water consumption outdoors (31%) during 2004–2008 (Hermitte & Mace, 2012). Regional water governance became increasingly attentive to anticipatory drought management over this period (Wilhite et al., 2000). For example, LCRA's 2007 water management plan tied combined reservoir storage at Lakes Travis and Buchanan to a schedule of increasingly stringent, mandatory residential outdoor water use restrictions, which would become a signature element of Austin's response to the recent drought (Sanson, 2008).

2.3. 2008 to Present: Anthropogenic Drought and Mandatory Irrigation Curtailment

Beginning in 2008, precipitation deficits and high temperatures led to meteorological drought and water stress throughout the Colorado River Basin, which reached peak severity in 2011 and were alleviated by heavy rains in spring 2015 (Austin Water Utility, 2015). Combined reservoir storage hovered just above 30% of capacity over much of 2011–2015, a result of persistently low inflows in conjunction with an agricultural release of over 0.53 km^3 (433,000 ac ft) of water to downstream rice farmers in spring 2011, roughly triple Austin's annual withdrawal (Gooch et al., 2011). Following this release, LCRA amended its water management plan to withhold water from rice growers for the years 2012–2015 while allowing limited environmental flows to Matagorda Bay, but persistently low reservoir levels compelled Austin to implement a variety of emergency water conservation measures for much of 2009 to present, including an unprecedented once-per-week watering restriction that remained in place 2011–2015, as well as water price increases (Brown, 2014). Given the interactions between agricultural releases, urban water use, reservoir management, and potential impacts of climate change, watershed-scale drought during this period can be considered anthropogenic, in that it resulted from a combination of human and natural factors (Van Loon et al., 2016).

The perception of urban ecological impairment stemming from anthropogenic drought made outdoor watering restrictions politically contentious over the 2011–2015 period. Local drought impacts thought to be worsened by irrigation curtailment include heightened risk of fire (Water Environment Research Foundation, 2014); vegetation loss, particularly losses to the tree canopy (Cabrera et al., 2013); parched soils causing sewer main breaks that contaminate groundwater (Blue et al., 2015); worsened urban heat island effects; and reduced air and water quality (Austin American-Statesman, 2011). Affluent households, including a number of prominent elites, resisted once-a-week watering by refusing to comply with restrictions or by drilling their own wells into the Edwards Aquifer (Satija & Root, 2013). The severity of this drought has led to calls for prosperous, highly developed cities like Austin to reduce outdoor water use in anticipation of persistent reductions in water availability under climate change (AghaKouchak et al., 2015). Indeed, Austin officials proposed making the highly contested 2011–2015 restrictions a permanent feature of water governance to anticipate future drought linked to global climate change (Ott, 2015), although this proposal was relaxed following public engagement. Missing from this ongoing debate is an integrative analysis of the complex, coupled, and multiscalar sociohydrological effects of mandatory irrigation curtailment on urbanized systems with a history of anthropogenic contributions to the urban water cycle.

3. Data and Methods

We began our analysis of Austin's recent outdoor water conservation efforts by conceptualizing urban water withdrawal as a variable shaped by social and biophysical processes at multiple scales nested within a watershed-scale sociohydrological system. We analyzed the system as a whole using structural equation modeling, complemented by fine-scale statistical analysis of social and biophysical components at submunicipal scales, as outlined below. Data used in our study are summarized in Table 1, with detailed descriptions on data collection and processing in the supporting information.

3.1. Structural Equation Modeling

In H1, we hypothesized that conservation would be associated with significant shifts in the relationships among drought indicators, water withdrawals, and downstream flow at the municipal and watershed scales.

We tested H1 using structural equation modeling (SEM), which offers a holistic means to account for changes in linkages among interdependent variables that comprise a system. For the Colorado River Basin,

Table 1
Summary of Collated Social and Environmental Data Sets Used for This Research

Data category	Data	Spatial scale	Temporal extent	Data source	Hypothesis
Meteorology	Standardized Precipitation Evapotranspiration Index (SPEI)	$0.5° \times 0.5°$ grid	1901–2013	CRU TS 3.22[a]	H1
	Monthly temperature and precipitation to calculate urban SPEI	Weather station (GHCN #USW00013958)	1938–2015	NOAA GHCN-Daily Network[b]	H1, H2, H3
Streamflow	Daily discharge and water level	Gauge station (Figure 1 and supporting information Table S1)	1980–2015	USGS NWIS[c]	H1, H3
Lake level	Historical lake level	Lake Travis and Buchanan	2000–2015	LCRA[d]	H1
Water use	Monthly municipal water withdrawals	Municipal	2000–2014	Illinois Data Bank[e]	H1, H2
	Single-family residential water use	Zip code	2012–2015	City of Austin[f]	H3
Urban vegetation	Enhanced Vegetation Index	$250\ m \times 250\ m$ grid	2000–2015	NASA MODIS[g]	H1, H2
Sociodemographics	Sociodemographic and housing characteristics	Zip code	2009–2013	US Census ACS[h]	H2

Data sources: [a]CRU TS 3.22: Climate Research Unit (2014). [b]NOAA GHCN-Daily: Global Historical Climatology Network-Daily (National Climatic Data Center, 2015). [c]USGS NWIS: US Geological Survey National Water Information Service; available at https://qwwebservices.usgs.gov/portal.html. [d]LCRA: Lower Colorado River Authority (2016). [e]Illinois Data Bank: https://databank.illinois.edu/datasets/IDB-8503612. [f]City of Austin Data Portal: https://data.austintexas.gov/Utility/Austin-Water-Residential-Water-Consumption/sxk7-7k6z. [g]NASA MODIS: National Aeronautics and Space Administration (2016) MODIS Imagery; available at https://modis.gsfc.nasa.gov/. [h]US Census ACS: US Census Bureau American Community Survey; available at https://www.census.gov/programs-surveys/acs/.

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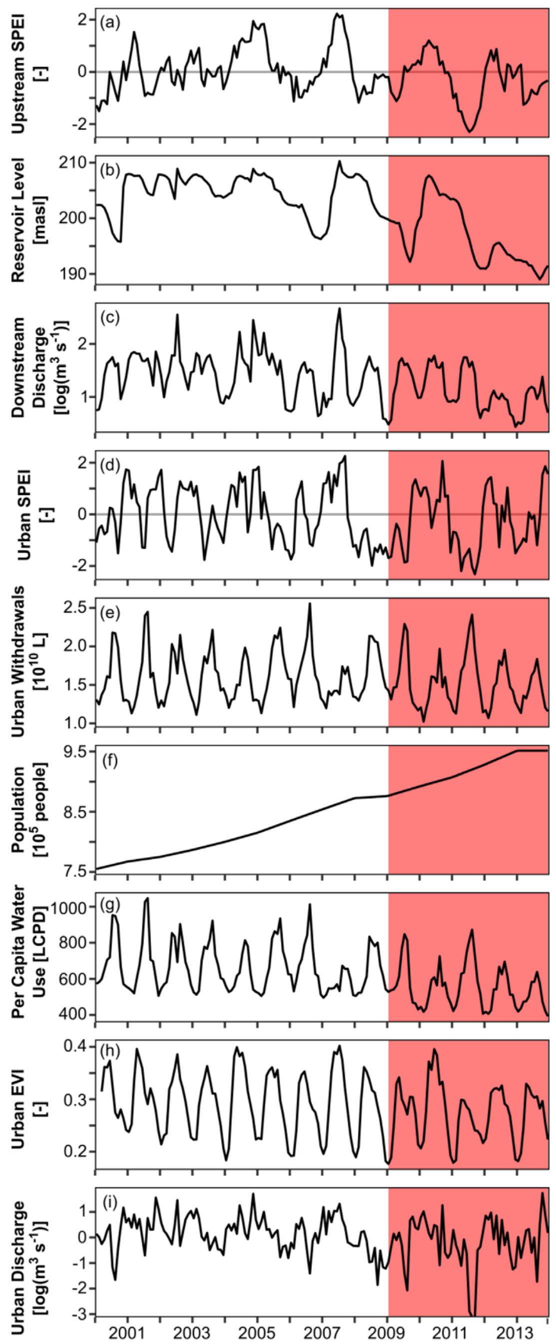

Figure 2. (a–i) Monthly time series plots for selected sociohydrological variables. Red-shaded area denotes two time periods: before (2000–2008) and during (2009–2013) the drought. (a) 6 month standard precipitation evapotranspiration index (SPEI) averaged over watershed upstream of Austin; (b) Lake Travis reservoir levels; (c) Colorado River discharge downstream of City of Austin; (d) 3 month SPEI for City of Austin; (e) City of Austin urban water withdrawals; (f) Austin Water Utility service area population; (g) per-capita water use for City of Austin (liters per capita per day); (h) City of Austin mean enhanced vegetation index (EVI); (i) total discharge into Colorado River from urban subwatersheds. With the exception of per-capita water use (Figure 2g), these data serve as inputs for structural equation modeling (sections 3.1 and 4.2).

we defined our sociohydrological system to include the upstream water source area, the storage reservoirs, the City of Austin water-using area, and downstream flows for environmental and agricultural users (Figure 2). We used SEM to assess how drought-induced water conservation may alter relationships between upstream drought, municipal-scale water availability and use, and downstream flow at the watershed scale, while simultaneously testing for shifts in relationships among water use, urban vegetation, and urban streamflow at the municipal scale.

Prior to fitting the SEM, we constructed a path diagram to define linkages among processes related to upstream water source areas (upstream climate and flow), urban water provisioning (reservoir levels and municipal water withdrawals), in-city water distribution (urban climate, vegetation, and streamflow), and downstream water flow. Details on our process to formulate this diagram are provided in the supporting information; the final path diagram is available in section 4.2 (Figure 5). We subset the data into two periods, before (2000–2008) and during (2009–2013) water restrictions, and fit a SEM model of the same structure to each period. We then compared coefficient estimates from the "before" and "during" SEM models, attributing coefficient changes to be the result of urban water conservation measures and drought. Due to a lack of data, we were not able to separate out effects of different types of water conservation programs, e.g., price effects versus outdoor watering restrictions (Mini et al., 2014).

For each period, we decomposed time series data to remove seasonality and temporal autocorrelation. We used the "decompose" function in R 3.3 to separate each time series variable into three components: seasonality, trend, and residual. For each variable, we used the addition of trend and residual components for analysis (i.e., excluding seasonality). All variables were then standardized so that coefficient estimates were comparable. We fit the SEM using "sem" function in the Lavaan package in R with maximum likelihood estimation. Model fit was measured using comparative fit index (CFI) because this index takes account of sample size and also performs well with small samples (Hooper et al., 2008).

3.2. Hierarchical Linear Regression Modeling

In H2, we hypothesized that water conservation would be associated with reduced "greenness" in urban vegetation over time due to restrictions on outdoor irrigation.

We tested H2 by developing a hierarchical linear regression model to explain variation in a panel data set of zip code-level vegetation estimates, measured using the enhanced vegetation index (EVI) in residential areas. We used hierarchical linear regression to leverage the inherent nested data structure of mesoscalar panel data; here a time series of EVI observations were nested within each zip code (Gelman & Hill, 2007). As with the SEM model, we used the "decompose" function in R to remove seasonality from time series variables and isolate trends in relationships over time. All variables were then standardized so that coefficient estimates were comparable. The resulting data set contained 32 EVI estimates, from July 2012 to December 2014, for 44 zip codes.

The hierarchical linear model was developed and specified using the "lmer" function in the lme4 package in R (Bates, 2010). Candidate fixed effects explanatory variables included monthly weather and climate data (mean maximum temperature, precipitation depth, and SPEI), mean zip code-level single-family residential (SFR) water use, zip code-level sociodemographic variables (age, race, income, and poverty rates), and zip code-level land use summary statistics (SFR lot area, building area, and property values). These variables were selected using prior knowledge of factors shaping urban vegetation. Detailed information on these data is provided in the supporting information.

We developed the fixed effects portion of the model through an iterative process of forward and backward selection, using the Akaike Information Criterion to determine which set of candidate variables better explained EVI along with the "anova" function to assess significant differences between alternate model configurations. We restricted maximum likelihood estimation to explore random effects among these variables. We also tested the significance of random effects involving these variables as well as all possible interaction terms among fixed effects. Finally, we included a duration variable ("time"), given in months relative to the first time period, to account for the effect of sustained irrigation restrictions on EVI. Decreasing EVI values over time (negative coefficient for "time") would indicate would support our hypothesis that irrigation restrictions negatively affected vegetation, after accounting for meteorological effects. Bootstrapped *p*-values (1,000 simulations) were generated for fixed effects coefficient estimates in the final model. An equation for the functional form of this model is provided in the supporting information.

3.3. Correlation Analysis

In H3, we hypothesized that restrictions on urban outdoor irrigation during drought decreased the amount of groundwater recharge, which would manifest in lower total streamflow, lower baseflow, and increased drought sensitivity in urban streams.

To quantify long-term shifts in hydrological drought sensitivity, we focused on a group of subwatersheds of the Colorado River fully or partially contained within City of Austin that have an uninterrupted record of $\geq$30 years (Figure 1 and supporting information Table S1). We quantified the hydrological drought sensitivity for each of these subwatersheds as the slope of a linear relationship between the annual number of hydrological drought days and annual precipitation. As our subwatersheds included a mixture of both ephemeral and perennial streams, we used the approach of van Huijgevoort et al. (2012) to identify hydrological drought days, defining hydrological drought as flow below the 80% exceedance probability. To test for changes in drought sensitivity resulting from water restrictions, we split our data into prerestriction and during-restriction windows (1986–2008 and 2009–2015, respectively). A change in hydrological drought sensitivity would manifest as a significant change in the slope of the relationship between hydrological drought days and annual precipitation. As the slope of the relationship between hydrological drought days and annual precipitation is negative (more hydrological drought days in years with lower precipitation), a more negative (steeper) slope in the during-restriction period would indicate increased drought sensitivity and support our hypothesis. For each of these subwatersheds, we also quantified the proportion of total streamflow derived from baseflow (the baseflow index; BFI) using the Web-based Hydrograph Analysis Tool (WHAT; Lim et al., 2005) parameterized using the default properties for ephemeral streams with porous aquifers.

To quantify the potential impacts of municipal water use on streamflow, we focused on eight urban headwatersheds. These headwatersheds were selected because they contained $\geq$75% residential land use serviced by the Austin Water Utility and had a continuous streamflow record from 2012 to 2015, to coincide with zip code-level water use data. Data on the magnitude and timing of withdrawals from private borewells are not available for Texas so private domestic water use was not considered (Bernstein, 2013; Perrone & Jasechko, 2017; Satija & Root, 2013). For this analysis, we resampled municipal water use data from zip code level to subwatersheds by weighting each of zip code's water used based on the proportion of that zip code's residential area contained within each subwatershed. We used linear regression between monthly total discharge and precipitation to quantify the climate component of monthly streamflow. We then tested whether including residential water use within that subwatershed improved the statistical relationship (as measured by adjusted R^2 to account for different numbers of variables) with streamflow. As the time it takes urban recharge to reach streams is unknown, we also test residential water use from the previous 1–12 months and determine which lags, if any, have the best predictive power for monthly streamflow.

4. Results

4.1. Spatial and Temporal Patterns of Water Use and Vegetation Within Austin

In Austin, the onset of anthropogenic drought and the urban water conservation response coincided with shifts in water availability, water consumption patterns, and ecohydrological variables at multiple scales. Upstream of Austin, SPEI declined following 2008, indicating drier upstream conditions, with a sharp drop in 2011 associated with the height of the drought (Figure 2a). While drier conditions upstream reduced water availability, drier conditions within the city (Figure 2d) increased water use, as illustrated by a peak in water withdrawals in 2011 (Figure 2e), which, in conjunction with the agricultural release discussed in section 2, resulted in declining reservoir storage (Figure 2b) following 2011. Severe drought in 2011 was also associated with troughs in urban EVI (Figure 2h) and urban streamflow (Figure 2i). However, following 2011, urban withdrawals began to fall, likely a result of water conservation, while urban ecohydrological variables began to recover. Effects of water conservation are particularly evident when comparing withdrawals to population; withdrawals by AWU have fallen from an average of 16.2 $\times$ 10^9 gal. (0.061 km^3) per day 2000–2008 to 14.9 $\times$ 10^9 gal. (0.056) per day (2009–2014; Figure 2e) even as population increased from 873,000 in 2009 to 951,000 in 2014 (Figure 2f). Likewise, comparing 2000–2008 to 2009–2014 periods, Austin's per-capita water use fell from an average of 666–541 L/d, more than offsetting the effect of population growth following 2008 (Figure 2g).

Within the city, reductions in water use were evident for all zip codes in the AWU service area 2012–2014 (Figure 3d) following the extreme drought conditions in 2011, with some zip codes reduced water use by over 30%. Over the same interval, zip code-level EVI increased across the majority of zip codes, although vegetation recovery was spatially uneven (Figure 3e). Reduced EVI was apparent in the southwest portion of the study area, where household incomes, water consumption rates, and vegetation were highest (Figures 3a–3c), a correlation that is consistent with previous studies showing income to be a primary factor shaping both urban irrigation practices and vegetated urban land cover (Mennis, 2006; Schwarz et al., 2015). Reduced EVI was also evident along the easternmost zip codes, a periurban area of high EVI but relatively average income and water use (Figures 3a–3c); in these zip codes, urban residential land uses are mingled with agriculture (Figure 1). Taken together, the patterns in Figures 2 and 3 indicated that urban water conservation in response to anthropogenic drought was associated with reductions in urban water

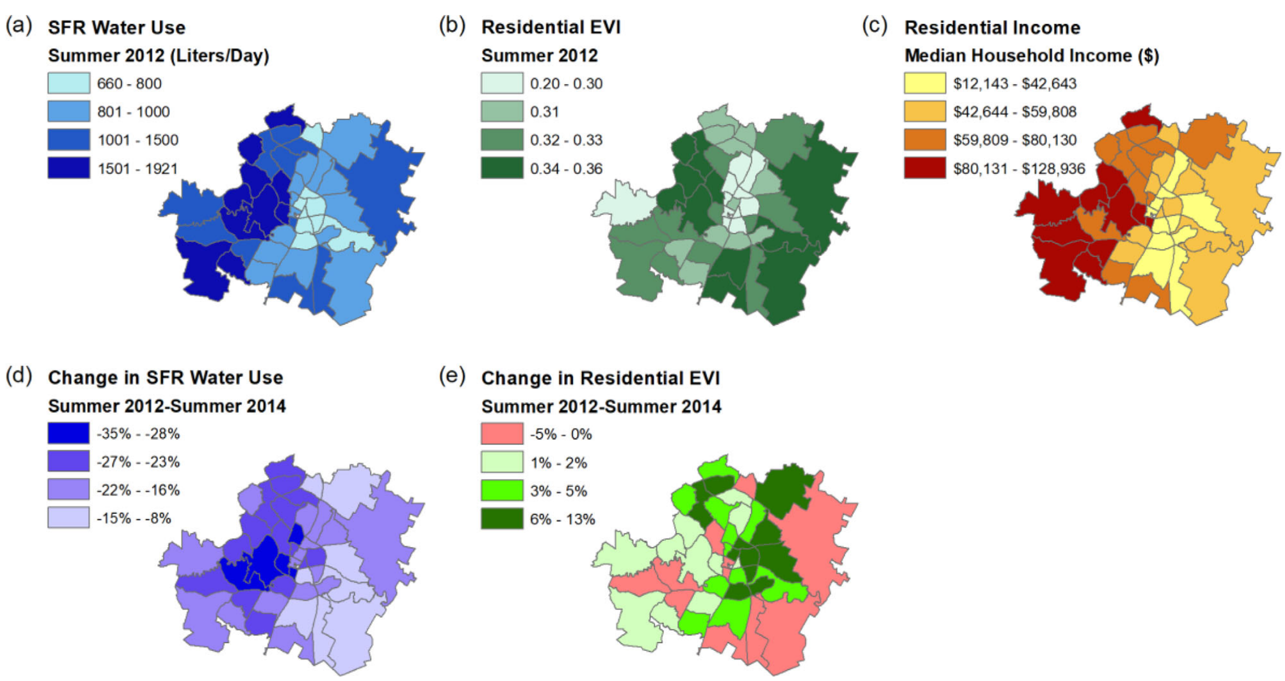

Figure 3. (a–e) Zip code-level maps of residential water use, vegetation, and income in City of Austin. (a) Mean single-family residential (SFR) water use in summer (June–August) 2012, (b) mean enhanced vegetation index (EVI) in summer (June–August) 2012, (c) median household income, (d) percent change in summer SFR water use (2012–2014), and (e) percent change in summer EVI (2012–2014).

withdrawals, even as population increased, mirrored by decreasing residential consumption alongside a gradual, though spatially uneven, process of urban vegetation and streamflow recovery from drought.

4.2. Shifts in Sociohydrological Coupling Under Mandatory Water Conservation

Prior to water use restrictions, SEM results showed that the Austin system was characterized by significant watershed-scale coupling among upstream drought, municipal water availability and use, and downstream water flow (Figure 4). Significant, positive paths were found between upstream SPEI to reservoir levels (arrow B2; effect size = 0.53) and between upstream SPEI and downstream water flow (B1; effect size = 0.30). In addition, we detected a positive path from upstream water availability to downstream water flow (B3; effect size = 0.16) and a negative path from upstream water availability to municipal water use (B4; effect size = −0.21). These results were as expected—more severe upstream drought conditions (indicated by lower SPEI values) led to reduced reservoir inflows, reducing municipal water availability and downstream flow.

During periods of mandatory water restrictions for reservoir management, SEM results indicated that Austin's water conservation efforts have coincided with a significant shift in how climate, water availability and use, and downstream flow interacted at the watershed scale (Figure 4). Specifically, the path from upstream drought to downstream water flow was no longer significantly different from 0 (D1; effect size = −0.26, $p = 0.14$). Moreover, the path from upstream water availability to municipal water withdrawal changed from significant to nonsignificant (D4; effect size = 0.05), suggesting that there was no longer a relationship between water availability and water use under conservation.

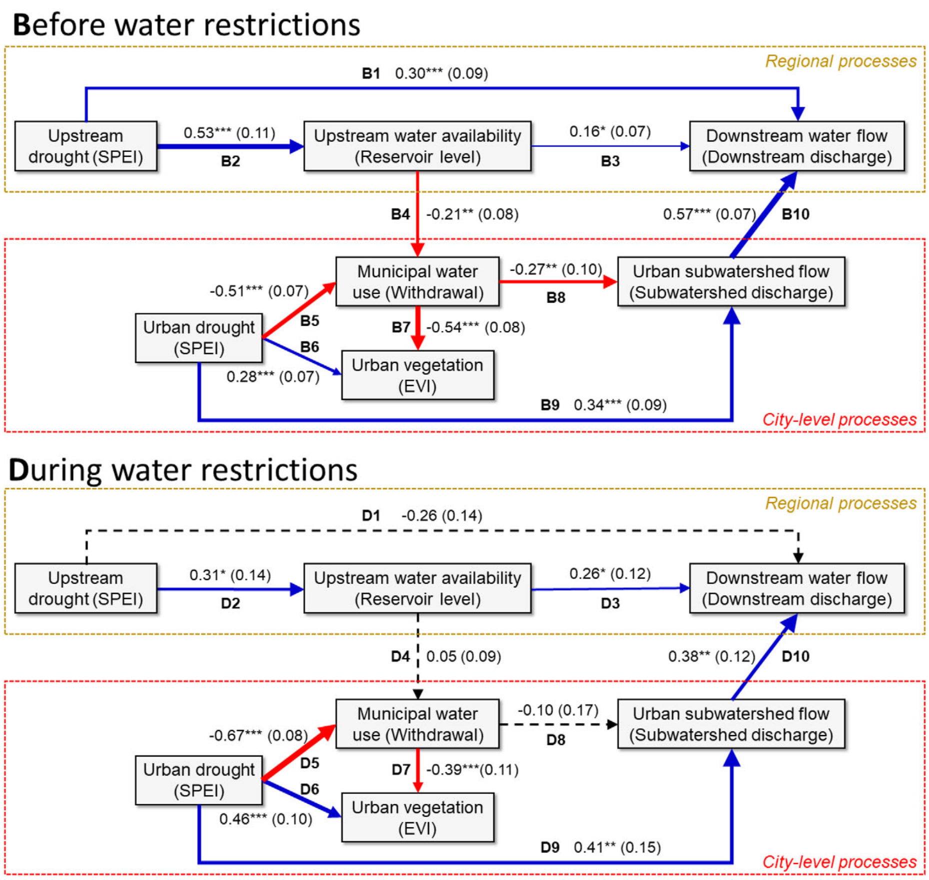

Figure 4. Results of structural equation modeling of regional and city-level hydrological responses to drought before and during the implementation of mandatory irrigation restrictions. Arrows are numbered, with "B" indicating a path before restrictions and "D" indicating the same path during restrictions. Red and blue arrows indicate significant paths (*$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$), with blue arrows indicating positive relationships and red arrows indicating negative relationships. Black dashed arrows indicate nonsignificant paths. The thickness of the arrow is proportional to effect size. The first number for each path is coefficient estimate and the number in parentheses are standard errors.

At the municipal scale, prior to drought-induced water conservation (Figure 4), SEM results revealed significant positive paths from urban SPEI to urban vegetation (estimated by EVI, B6; effect size = 0.28) and urban subwatershed flow (B9; effect size = 0.34), as well as a negative path from urban SPEI to municipal water use (B5; effect size = −0.51). During the same period, significant negative paths were detected from municipal water use to urban vegetation (B7; effect size = −0.54) and urban subwatershed flow (B8; effect size = −0.27) while a positive path from subwatershed flow to downstream water flow was observed (B10; effect size = 0.57). As with the regional scale, these findings were consistent with our hypotheses—more severe drought conditions (lower SPEI value) within the city led to reduced "greenness" in urban vegetation and reduced urban streamflow, as well as heightened urban water consumption.

Following implementation of outdoor water conservation, most municipal-scale relationships remained consistent with the exception of one linkage between municipal water use and urban subwatershed flow (Figure 4). Specifically, the negative path from municipal water use to downstream flow was decoupled during water use restrictions, with effect size changing from significant (B8; effect size = −0.27, $p = 0.10$) to nonsignificant (D8; effect size = −0.10, $p = 0.17$).

While useful for studying watershed-scale sociohydrological relationships, this approach and scale of analysis considered the city as a "black box" (i.e., single point of analysis). To explore municipal-scale variability in linkages among urban climate, water use, vegetation, and streamflow, we zoomed into the submunicipal scale with hierarchical linear modeling and correlation analysis (sections 4.3 and 4.4).

4.3. Urban Vegetation Drought Response Following a Socioeconomic Gradient

Through the process described in section 3.2, we arrived at a hierarchical linear regression model that explained zip code-level EVI as a function of meteorological variability (mean maximum monthly temperature, or TMAX, and urban SPEI), water use patterns (mean SFR water use), socioeconomic status (median household income), and duration of restrictions (time, given in months from start period). We also identified a significant interaction involving income, time, and EVI. The model incorporated two types of random effects; "random slopes" for urban SPEI, meaning that the effect of local drought conditions on vegetation varied by zip code, and "random intercepts" (reflecting mean EVI), meaning that variability in zip code-level vegetation fluctuated around mean values that were themselves allowed to vary by zip code. Most of the between zip code variance in EVI was located in the intercept term, interpreted as mean greenness by zip code. This indicated that, while EVI does change over time, it varies around a mean zip code-level EVI value that itself varies widely across zip codes.

Standardized coefficients for fixed effects from the hierarchical linear model are given in Table 2. Results indicated that EVI tended to decrease with higher temperatures (TMAX coefficient = −0.047, $p = 0.01$) and more severe drought conditions (SPEI coefficient = 0.168, $p < 0.001$), as expected. Precipitation was not included in the final model because of its close correlation with urban SPEI; we found the latter explained more variability in EVI at a monthly time step. A negative relationship was found between EVI and SFR water use (coefficient = −0.065, $p = 0.005$), consistent with the SEM model. This seemingly counterintuitive result arose performing a seasonal adjustment on EVI and SFR water use (as well as all other time-varying data) and because we included TMAX and urban SPEI in the model. After controlling for seasonality, weather, and climate, EVI and SFR water use are negatively related because additional irrigation replaces water lost to ET,

Table 2
Standardized Coefficient Estimates for Fixed Effects in Hierarchical Linear Regression Model

Variable	Coefficient	SE
Mean maximum monthly temperature (TMAX)	−0.047[a]	0.018
3 month standard precipitation evapotranspiration index (SPEI)	0.168[c]	0.022
Time (months)	0.051[a]	0.015
Mean monthly single-family residential (SFR) water use	−0.065	0.035
Median household income	0.359[b]	0.13
Median household income × time	−0.075[c]	0.012

[a]$p < 0.05$. [b]$p < 0.01$. [c]$p < 0.001$.

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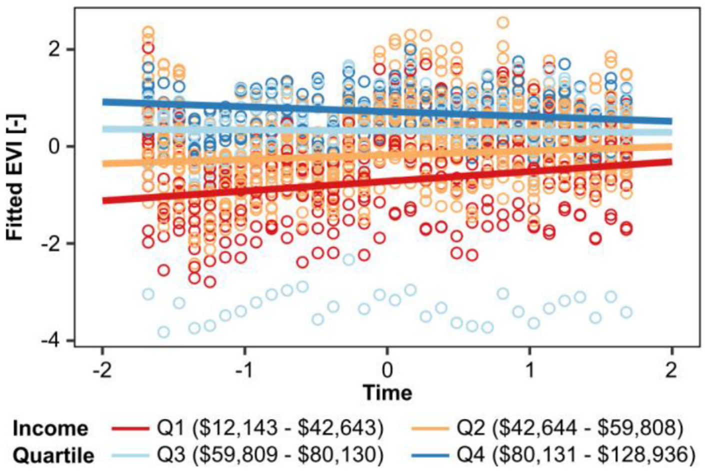

Figure 5. Interaction effect involving vegetation (enhanced vegetation index, EVI), median household income (by quartile), and time, as identified through hierarchical linear modeling. EVI was lowest for zip codes in the bottom income quartile (red) but increased even as mandatory irrigation restrictions remained in effect. By contrast, EVI was highest in the top income quartile (dark blue) but decreased over the same interval.

particularly at the high temperatures found under drought conditions. Median household income explained the bulk of variation in EVI (coefficient = 0.359, $p = 0.008$), consistent with previous research demonstrating a strong linkage between urban vegetation patterns and socioeconomic status—residential properties in more affluent areas tend to sit on larger lots with more abundant vegetation (Mennis, 2006; Schwarz et al., 2015).

The positive coefficient for time (coefficient = 0.051, $p < 0.001$) indicated that EVI has generally increased over the study period, accounting for meteorological effects, contrary to H2. However, a negative interaction was detected between median household income and time (coefficient = −0.075, $p < 0.001$), indicating that the rate of increase in EVI over time slowed as income increased; more affluent areas experienced slower vegetation recovery. Examination of the interaction term effect size (Fox, 2003) by income quartile (Figure 5) indicated that, for zip codes in the bottom two quartiles of the income distribution, EVI had increased over time. By contrast, zip codes in top income quartile tended to experience reductions in EVI. These results indicated that the effect of outdoor water conservation on urban vegetation varied spatially but generally followed a socioeconomic gradient, with negative effects on vegetation primarily concentrated in affluent areas on the west side of the study area. However, several zip codes characterized by mixed urban and agricultural land uses along the eastern periurban periphery also experienced reductions in vegetation, which we discuss in section 5.

4.4. Heterogeneous Urban Streamflow Drought Response

We further analyzed effects of outdoor water conservation on streamflow within the City of Austin. Due to the regional northwest to southeast slope of the Austin area, watersheds tend to cut across both more and less affluent regions, and thus encompass varying degrees of water use and conservation. In all watersheds, the relationship between hydrological drought and annual precipitation was statistically significant ($p < 0.05$) for the prerestriction period (1985–2008; Figures 6a–6e). During restrictions (2009–2015), the relationship between hydrological drought was significant at Shoal Creek and Walnut Creek ($p < 0.05$), with negative but not significant correlations at Barton Creek ($p = 0.136$), Bull Creek ($p = 0.066$), and Onion Creek ($p = 0.078$). While drought sensitivity increased visually in the Bull Creek and Walnut Creek subwatersheds (Figures 6b and 6c; steeper line during restrictions compared to prerestrictions), no subwatershed showed significant differences in slope between periods, indicating that effects of water restrictions on hydrological drought occurrence cannot be distinguished from random variation.

Interestingly, however, interannual variability in hydrological drought is more strongly associated with precipitation in the during-restriction period compared to the prerestriction period. Prerestriction, adjusted R^2 values range from 0.25 to 0.36 for our five subwatersheds; during restriction, the adjusted R^2 values are higher at four of the five watersheds (all except Barton Creek) and range from 0.26 to 0.56, despite the

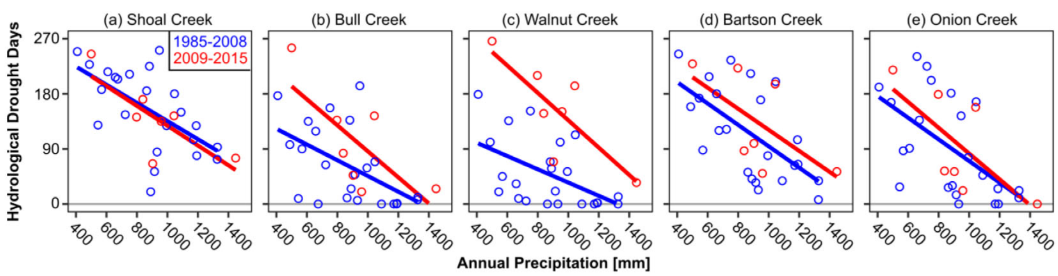

Figure 6. (a–e) Sensitivity of hydrological drought, calculated as in van Huijgevoort et al., (2012), to mean annual precipitation for each of the urban subwatersheds with long-term data (Figure 1). Plots are divided into prerestriction (blue) and during-restriction (red) periods.

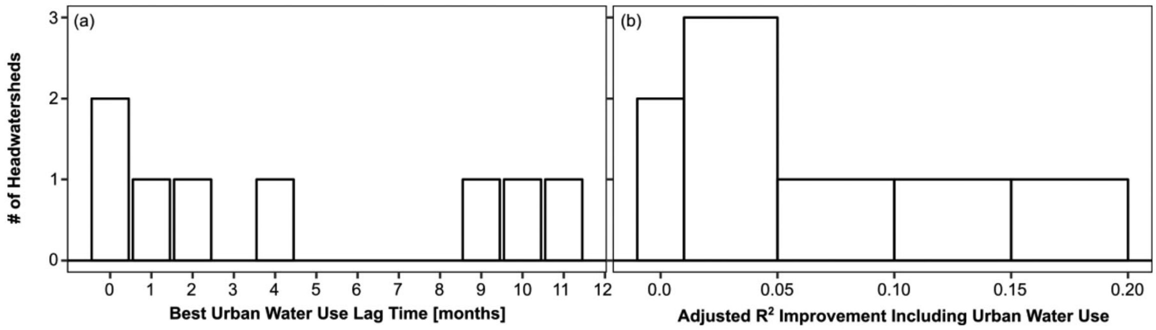

Figure 7. (a) Number of prior months of urban water use that produces the best relationship between streamflow = f(precipitation, water use) for the eight subwatersheds in Figure 1; a lag time of 0 months means that precipitation alone is the best predictor of streamflow. (b) The improvement to the adjusted R^2 of streamflow = f(precipitation, water use) linear relationships when including urban water use, as compared to only precipitation.

smaller number of data points available in the during-restriction period. The indicated of these two populations are different at $p = 0.05$ (Welch two-sample t test). The observed shift toward higher R^2 values during restriction indicated that the presence or absence of hydrological drought became more strongly associated with interannual climate variability, which agrees with SEM results showing an increase in coefficient strength during restrictions. We inferred that this finding may be associated with a reduction in groundwater discharge to streams, which can play a buffering role on streamflow during low precipitation conditions. However, we could not attribute the result exclusively to water use restrictions, as a natural depletion of aquifer levels as a result of drought may also be contributing to the stronger observed coupling between streamflow and precipitation following 2008.

To determine whether there was a significant relationship between residential water use and streamflow, we tested whether including water use improved the relationships between monthly streamflow and precipitation for eight headwatersheds within the City of Austin. Results indicated that including residential water use improved the strength of the relationship in most subwatersheds analyzed, with variability in both lag time and degree of improvement (Figure 7). In six of the eight headwatersheds, including residential water use improves the prediction of monthly streamflow patterns when compared to precipitation alone, with lags varying from 0 to 11 months (mean = 4.6 months; significant different from 0 at $p = 0.03$) However, in most cases improvements were small; at three of the six headwatersheds where considering residential water use led to an improvement, the change in adjusted R^2 was <0.05, though one watershed in the southwest portion of Austin had an increase in adjusted R^2 of 0.16 relative to baseline conditions. These results suggested that municipal water use contributed to streamflow within urban subwatersheds, but precipitation remained the dominant driver of variability.

Hydrograph separation results for the urban subwatersheds with long-term data indicates variable contributions of baseflow to mean annual streamflow, with baseflow index estimates ranging from 9 to 38% (supporting information Table S1). While baseflow index did not appear to vary as a function of affluence, streamflow in areas where baseflow is a higher proportion of total annual flow may be more vulnerable to negative impacts of groundwater pumping. As noted in section 2, some wealthier households subverted outdoor water conservation efforts by drilling private wells to water their lawns in excess of restriction levels. Due to the hydrogeological principle of capture of discharge (Bredehoeft, 2002; Gleeson & Richter, 2018), this likely had a negative effect on local groundwater discharge to streams, which may have the negative consequence of reducing flow, particularly during drought.

5. Discussion

Our study investigated urban water conservation as a sociohydrological response to watershed-scale drought, focusing on how water conservation, and particularly irrigation curtailment, affected local ecosystems and the broader watershed. We found mixed support for our hypothesis that urban water conservation has altered sociohydrological interactions at watershed and municipal scales. SEM results demonstrated that streamflow processes upstream and downstream of Austin decoupled as urban and rural irrigation was curtailed to maintain reservoir storage (Figure 4 and section 4.2). Within the city, vegetation

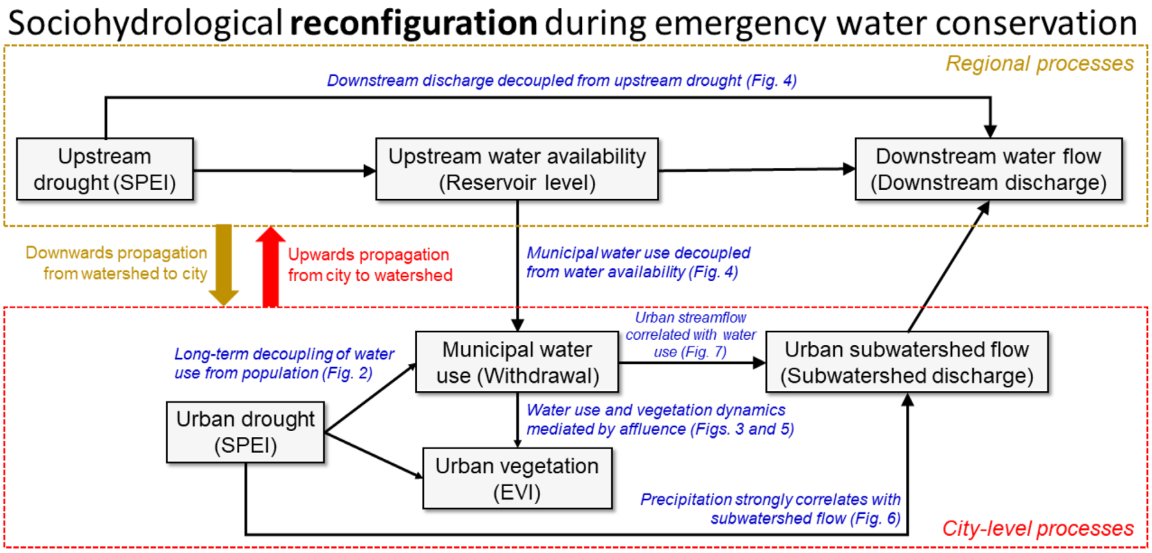

Figure 8. Reconfiguration of cross-scale relationships within an integrated urban-regional sociohydrological system during mandatory irrigation restrictions as emergency water conservation strategy during anthropogenic drought.

drought recovery varied spatially, with negative effects largely confined to relatively affluent, heavily irrigated areas and the periurban periphery (Figures 3 and 5 and section 4.3). While our analysis did not indicate that the relationship between streamflow and precipitation changed following water restrictions (Figure 6), we did find some evidence to support the hypothesis that water conservation negatively impacted urban streamflow, as urban streamflow was related to water use in six of eight watersheds (Figure 7 and section 4.4). Additionally, high baseflow in many urban subwatersheds suggested that conservation-driven reductions in groundwater availability may further increase drought sensitivity of urban streams (supporting information Table S1). Finally, we observed an unexpected inverse relationship between population growth and water withdrawals over the study period (Figure 2 and section 4.1), which we discuss below as we synthesize results by offering three main findings on cross-scale effects of outdoor water conservation in urbanized systems; this synthesis is displayed graphically in Figure 8.

5.1. Reservoir Management and Urban Water Conservation Reconfigure Cross-Scale Relationships Among Elements in a Sociohydrological System During Drought

Comparing SEM results before and during the drought (Figure 4 and section 4.2), we identified two key cross-scale interactions involving Austin and the Colorado River watershed. First, at the watershed scale, drought conditions upstream of Austin and Colorado River discharge downstream of Austin decoupled, going from a significant positive relationship prior to 2009 to insignificant from 2008 onward. After peak drought severity in 2011, upstream drought conditions were somewhat improved 2012–2013 (upstream SPEI increased) but downstream discharge decreased as LCRA sought to avert further losses in reservoir storage by curtailing agricultural irrigation releases (Figure 2 and section 2). Second, reservoir levels and Austin's municipal water withdrawals decoupled during drought, going from negative to insignificant during the drought (Figure 4). Previously, low reservoir levels were linked with higher urban water withdrawals, both likely driven by meteorological drought (upstream and urban SPEI, respectively; Figure 4). However, during the drought, and particularly after 2011, reservoir levels and water withdrawals decreased together (Figure 2), with the former a result of low inflows and the latter a result of urban water conservation. We argue these two cross-scale changes, decoupling the relationship between upstream drought and downstream flow as well as between urban water availability and use, constitute a reconfiguration of the sociohydrological system (Figure 8). The city—or, more specifically, the city's reservoir system and conservation efforts—acted as a decoupling point for (1) watershed-scale water movement above and below the reservoir and (2) the linkage between Austin's municipal water withdrawals and the processes driving watershed-scale water supply.

Detailed analysis of individual components of the municipal water cycle provided evidence that the decoupling of water availability from water use produced effects that were spatially uneven with respect to urban ecohydrological variables. The vegetation analysis found that the rate of vegetation drought recovery tended to vary as a function of income, with the most affluent (and heavily irrigated) areas experiencing some losses in vegetation while other areas experienced minor recovery (Figure 5 and section 4.3). The hydrological analysis found that urban subwatershed streamflow was more responsive to precipitation during restrictions than before (Figure 6 and section 4.4), suggesting that urban water cycle became more strongly coupled to interannual meteorological variability during the drought. The relationship between zip code-level water use and streamflow in the majority of the headwatersheds studied (Figure 7 and section 4.4) indicated that this may be due to a decrease in anthropogenic influence on hydrological processes. In other words, reducing urban water use through conservation also has the effect of spatially redistributing how water flowed across urban space which, in turn, affected ecohydrological processes such as vegetation growth and streamflow that depend on these anthropogenic water contributions.

5.2. Affluence, Rather Than Population, May Drive Urban Water Stress in Developed Economies During Anthropogenic Drought

Urban population growth has historically been a core driver of water stress, but evidence from Austin demonstrates that urban water withdrawals have recently decoupled from population (section 4a). Indeed, many US cities have recently undergone a similar transition—urban water withdrawals are falling as population continues to grow (Brelsford & Abbott, 2017; Mayer et al., 2015; Zipper et al., 2017a, 2017c). Much of the shift has been attributed to passive indoor water conservation through technological change toward more water-efficient appliances, allowing declining rates of per-capita water use to outstrip population growth (DeOreo et al., 2016; Rockaway et al., 2011). Hughes et al. (2013) argue that, following this transition away from population-driven water use in developed economies, urban vulnerability to drought stems primarily from how cities are exposed to the confluence of climate, regulatory, and political stress, rather than from raw population growth.

Integrating this insight with the study area narrative (section 2) and the vegetation analysis (section 4.3), we propose that urban affluence, rather than population growth, comprises a core driver of spatial variability in water stress amid Anthropogenic drought in developed, urbanized systems like Austin. Results indicated that the most affluent neighborhoods in Austin consumed the most water prior to the drought, reduced water use the most during the drought (over 30% over a 2 year period), and, as a result, saw the least relative recovery in vegetation. Conversely, less affluent areas tended to use less water outdoors, so the effect of conservation on vegetation drought recovery was less pronounced. These findings are consistent with previous studies demonstrating that affluent households in both Los Angeles, CA, and Aurora, CO, use more water and conserve more water during irrigation restrictions (Kenney et al., 2008; Mini et al., 2014). Given the key role vegetation plays in the urban water and energy balance, varying patterns of urban water conservation likely have implications for submunicipal variability in temperature (Oke, 1982, 1988), vegetation productivity and water use (Zipper et al., 2016, 2017a, 2017c), and human wellbeing (Hartig & Kahn, 2016; Kuo & Sullivan, 2001). These results further support previous research indicating that the relationship between urbanization and water resources will be strongly dependent on submunicipal-scale heterogeneities, such as household-level decisions (Srinivasan et al., 2013). Because urban water use patterns are highly uneven within cities, securing future reductions in use will require managers to shift focus from city-wide population-based summary statistics to spatially explicit submunicipal measures of water use in relation to socioeconomic variables in order to target heavily irrigated, typically affluent neighborhoods within their service areas.

However, outdoor water conservation may also generate political stress because urban irrigators may fail to comply with outdoor water conservation efforts (Ozan & Alsharif, 2013). The case of Austin demonstrates that some affluent households may be willing to strenuously contest or subvert irrigation restrictions, introducing new forms of political feedback into the sociohydrological system. From this, we suggest that outdoor water conservation as reservoir management strategy during times of anthropogenic drought may trigger novel forms of community sensitivity and political contestation, particularly in systems adapted to excess irrigation contributions becoming return flow, as specific (and perhaps powerful) user groups are asked bear the local negative ecohydrological impacts of water conservation in the interests of system-wide resilience (Chen et al., 2016; Elshafei et al., 2014).

5.3. Biophysical Effects of Urban Water Conservation Propagate Within the City and Across the Watershed

Based on these findings and our study area narrative (section 2), we suggest that the ecohydrological effects of water conservation can cascade "upward" from the city across the watershed (reconfiguring water flow above and below the reservoir; section 5.1) and "downward" (by redistributing water within the city; section 5.2) during times of anthropogenic drought (Figure 8). Declining reservoir storage, resulting from both watershed-scale drought and municipal water use and worsened by the 2011 agricultural releases to downstream rice growers (section 2), triggered unprecedented urban water conservation efforts alongside curtailment of agricultural releases to downstream rice farmers. However, the effect of mandatory irrigation curtailment was uneven across space. Instead, irrigation curtailment was greatest for affluent urban households in Austin and downstream rice producers, altering how both irrigator groups interacted with and affected their water source. As water managers curtailed urban and rural irrigation to maintain reservoir storage, the repercussions of these decisions propagated inward (within the city) to both reduce and redistribute water flow, affecting terrestrial and aquatic ecosystems within Austin, and outward (across the watershed) to decouple discharge downstream of the city from drought in the watershed.

Because water use restrictions can rapidly reduce and redistribute water at municipal and watershed scales, we argue that cities may be a key point of control over intersectoral water allocation, particularly in relatively prosperous sociohydrological systems of the Global North in which urban irrigation currently comprises a relatively large share of total urban withdrawals. In the Colorado River Basin, intersectoral conflict increased during water restrictions because, while urban irrigation was regulated, agricultural irrigation was effectively banned due to its lower economic importance; in contrast, work in agriculturally dominated watersheds has demonstrated that urban water use restrictions are an effective tool for reducing intersectoral conflict during drought (Zipper et al., 2017b). However, because of the likelihood that sustained anthropogenic drought will become the "new normal" in Texas, we speculate these dynamics may ultimately push the Colorado River Basin toward a future system state in which irrigated vegetation is supplanted by drought-tolerant, rain-fed vegetation for both urban and agricultural irrigators. Furthermore, sustained outdoor water conservation may also introduce new forms of "demand hardening" by eliminating flexible water uses that serve as a key conservation lever, thereby reducing the ability to rapidly reduce urban water withdrawals during future droughts, while also depriving urban water providers of revenue (Kenney, 2014).

5.4. Study Limitations

In contrast to other sociohydrology approaches that favor long time horizons, we considered less than two decades of data, limiting our ability to project future system states. However, our study enriches prior sociohydrology approaches by adding a spatially explicit analysis on fine-scale heterogeneity in sociohydrological processes. Although a longer time frame may have led to more robust results, we argue that the drought can drive the study system to a new state over a relatively short time period, particularly with respect to the effect of population on withdrawals. Moreover, although outdoor water use restrictions were at the heart of Austin's governance response to anthropogenic drought, this policy was implemented alongside a host of other conservation programs, several adjustments to the water billing structure, and intensive conservation outreach. Given the lack of sufficient data on other programs, we were unable to separate how these various components of urban water conservation affected urban water withdrawals or zip code-level residential water use.

6. Conclusions and the Future of Urban Sociohydrology

In this study, we demonstrated that outdoor water conservation during anthropogenic drought can act as a reservoir management strategy that both influences and responds to hydrological processes, initiating a cascade of cross-scale interactions and feedbacks across watershed, municipal, and submunicipal scales. Within the city, outdoor water conservation redistributed water, producing some deleterious ecohydrological impacts at submunicipal scales, but these effects were spatially heterogeneous, relatively small in their magnitude, and fall disproportionately on more affluent urban residents. Our results may assist water resource managers in balancing a host of competing priorities associated with drought management, highlighting the effectiveness of short-term curtailment of water use and the need to consider submunicipal socioeconomic drivers of water use, rather than relying solely on water price increases.

Understanding such cross-scale interactions and political feedbacks is essential to both studying and managing regional water resources as coupled sociohydrological systems. We argue that understanding anthropogenic drought in urbanized systems will require hydrologists to open up the "black box" of the city by developing a specifically *urban* sociohydrology, in which water conservation is understood as a multiscalar, spatially explicit drought response that arises from and feeds back into a coupled human-environmental system (Dermody et al., 2018). Outdoor water use has been characterized as a complex climate adaptation problem and the "next frontier" in urban water conservation in developed economies (Gober et al., 2016; Mayer et al., 2015). Sociohydrology's focus on two-way feedbacks and cross-scale interactions are particularly relevant to grappling with the intricate, multiscalar couplings that shape how urban water use influences the urban water cycle (Srinivasan et al., 2010, 2013). Understanding how these issues of scale and political constestation interact with hydrological processes will require the integration of hydrological models with fine-scale models of variation of urban water use in relation to land use, socioeconomic status, and other factors within cities, alongside detailed qualitative analysis (Treuer et al., 2016)

Given these strengths and challenges, our analysis highlighted several future directions for urban sociohydrology. First, we identified the need to treat urban areas as heterogeneous with spatially variable responses to environmental stressors. While urban areas are often modeled with a single parameter, e.g., community sensitivity (Elshafei et al., 2014), our work shows that community sensitivity may itself vary spatially as a function of socioeconomic variables such as income. Second, we highlighted the need for ongoing engagement between hydrology and the social sciences to govern water resources. Encouraging prosperous, urbanized systems to shift away from irrigated landscapes and toward drought-tolerant vegetation requires basic research on how cultural practices drive household-scale irrigation patterns that influence basin-scale sociohydrological processes and, as a consequence, transitions to climate-safe societies (Shove & Walker, 2010). Finally, we concluded that incorporating human activities such as water use and water conservation into the water cycle requires integrative, trans-disciplinary research to tackle the increasingly complex cross-scale interactions and feedbacks that shape sociohydrological processes in the Anthropocene.

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