npj | urban sustainability

Article

Published in partnership with RMIT University

https://doi.org/10.1038/s42949-024-00144-1

Positive unintended consequences of urbanization for climate-resilience of stream ecosystems

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Developing sustainable urban systems is a fundamental societal challenge for the 21st century, and central Texas faces particularly synergistic challenges of a rapidly growing urban population and a projected increasingly drought-prone climate. To assess the history of urbanization impacts on watersheds here, we analyzed 51 cores from bald cypress trees in paired urban and rural watersheds in Austin, Texas. We find a significant contrast between rural and urbanized watersheds. In the rural watershed, tree-ring-width growth histories ("chronologies") from 1844–2018 significantly and positively correlate ($p < 0.01$) with (1) one another, and (2) regional instrumental and proxy records of drought. In the urbanized watershed, by contrast, chronologies weakly correlate with one another, with instrumental records of drought, and with the rural chronologies and regional records. Relatively weak drought limitations to urban tree growth are consistent with the significant present-day transfer of municipal water from urban infrastructure by leakage and irrigation to the natural hydrologic system. We infer a significant, long-term contribution from infrastructure to baseflow in urbanized watersheds. In contrast to the common negative impacts of 'urban stream syndrome', such sustained baseflow in watersheds with impaired or failing infrastructure may be an unintended positive consequence for stream ecosystems, as a mitigation against projected extended 21st-century droughts. Additionally, riparian trees may serve as a proxy for past impacts of urbanization on natural streams, which may inform sustainable urban development.

Population increases in urban areas are driving urban densification and expansion. By 2007, for the first time in human history, more people resided in cities than in rural areas[1] and this trend continues to the present day. This shift towards urban centers and changing climate can have synergistic negative impacts on the resilience of and services provided by watersheds and associated ecosystems, especially in terms of water quality and water availability. Understanding how water drives and links the natural, social, and engineered subsystems of urban centers is essential to developing sustainable urban systems. The resilience of water resources is stressed by both rapid growth and a changing climate, typified in many regions by increasing extremes in the hydrologic cycle. 21st century Texas is a sentinel community regarding these resilience challenges in that population growth (from 29.7 million in 2020 to nearly 51.5 million in 2070) and hydrologic extremes such as drought and flood are projected to increase significantly here[2,3].

To date, most of the research that addresses hydrology, geomorphology, water quality, and ecosystem function in urban systems can be broadly described in the context of "urban stream syndrome", a set of synergistic negative impacts on watersheds. Symptoms include diminished water quality due to nutrient loading and other anthropogenic pollutants, flashy and increased discharge during storms, and changes in stream geomorphology and stability[4–6]. Elevated concentrations of nutrients, heavy metals, herbicides, pesticides, and bacteria are ubiquitous in urban stream environments, particularly in areas where wastewater, animal waste, fertilizers, and herbicides enter the stream through point source and nonpoint source processes[7–10]. These aspects of urban stream syndrome help shape hydrologic science and infrastructure research agendas. There are significant drivers of urban watershed processes, however, that are not as widely identified or investigated, including some that may change the ecohydrologic system to yield positive unintended consequences. For example, the complex interactions between urbanization, climate, hydrology, and human behavior can result in positive consequences for urban stream ecosystem resilience[11], including reduced stream flashiness in arid settings[12], a

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weakening of the coupling between plant growth and water availability, and more temporally invariant ecosystem primary productivity[13]. One of these drivers is the age-related failure of water-supply networks and wastewater networks serving our cities, and the associated leakage of municipal supply water (i.e., non-revenue water) and wastewater[14]. For brevity, we will refer to non-revenue water and wastewater leakages collectively as "municipal water". Such consequences of urbanization—both positive and negative—are not well understood or, in some cases, even known. Our knowledge is limited in this area due to the lack of information on processes occurring on the decadal to century timescales relevant to urbanization changes. We explore these changes and consequences by developing tree-ring records, which have long been used as a paleoclimate proxy, for reconstructing temporal changes in riparian ecosystem response to watershed evolution.

We currently lack an understanding of (1) how to identify and quantify municipal water leakage in a time-, resource-, and technologically efficient way, (2) the transfer of municipal water from its infrastructure to the natural hydrologic system, (3) how this water evolves compositionally once in that system, and (4) the attendant impacts of this municipal water transfer on the resilience of urban hydrologic systems and the services they provide. Whereas significant losses of municipal water from infrastructure is a well-established phenomenon in many cities[15,16], only recently has progress has been made in (1) delineating how the losses vary between and within watersheds[14,17], (2) advancing the understanding of how these losses enter the natural hydrologic system, and (3) modeling the geochemical evolution of, and contaminant contributions from, this component of the hydrologic cycle[14,18]. These advancements pose the potential for new approaches, developed herein, for (1) assessing the impacts of infrastructure failure on hydrology and ecology, including previously unexplored unintended positive consequences, and (2) reconstructing the history of infrastructure failure through its impact on watershed hydrology and ecology. Having such new information on the past and current built environment will provide context for planning urban development under projected conditions for the remainder of the 21st century. This context includes design for more water- and energy-efficient water infrastructure, and assessment of tradeoffs between infrastructure and ecosystem services. Given the disparities in water quality and affordability, excessive heat impacts, and energy costs among different communities in each urban center, there are also social equity implications of such design and tradeoff decisions[19].

Here we use dendrochronology and compare the history of tree ring growth in two watersheds in the Austin, Texas region. We calibrate bald cypress (*Taxodium distichum*) records to modern instrumental records of drought and use these relationships to examine how urbanization affects their radial growth. We find a significant contrast between rural and urbanized watersheds: in the rural watershed, tree ring growth histories strongly reflect water availability controlled by regional drought variability, whereas the urbanized watershed tree ring growth histories correspond only weakly to records of regional drought variability. From these results, we infer a major, long-term contribution to baseflow in urbanized watersheds from municipal infrastructure that buffers against a more direct response to regional climate and drought. There are four inputs of water to riparian bank-side bald cypress trees in an urban watershed, either through direct inputs to the stream or input to soils adjacent to trees: (1) natural hydroclimatic inputs, (2) leakage inputs to streams from the municipal supply water network, (3) leakage inputs to streams from the wastewater network; and (4) irrigation inputs. Our study provides evidence for a component in addition to source 1 to streamflow from sources 2, 3, and/or 4 over the period of the tree-ring record. In this manner, riparian trees may serve as a proxy for the impacts of urbanization on natural streams.

We employ the proxy of tree ring growth rate, which has long been used for paleoclimate reconstruction, to reconstruct the impacts of urbanization on streamflow. This new proxy approach covers time periods concomitant with urban development and densification. We compare the radial growth rate of tree rings across a rural and urban watershed in Austin, Texas and use the climate sensitivities of the growth rates to interpret differences between the watersheds. Bald cypress trees occur in riparian, lowland, or wetland habitats in the southern United States from Delaware and Virginia through the Gulf Coast states[20]. Its growth-increment widths can be crossdated to generate annually resolved chronologies that strongly relate to moisture availability. As such, this species has been widely used to reconstruct precipitation and drought across the southeastern US and Texas[21–25]. In these applications, annual ring width has been positively associated with rainfall amount and resulting soil moisture variability.

Bald cypress have also been used to evaluate natural and anthropogenic changes in hydrologic regimes, such as subsidence following earthquakes[26], impacts of dam building, and the addition of supplemental wastewater to a lowland forest[27–29]. In central Texas, bald cypress is a major subdominant species in floodplain forests[30] with well-documented drought sensitivity in radial growth[25]. Further, bald cypress commonly grow along stream banks and direct much of their root growth into the streams. Thus, bald cypress are an ideal candidate for quantifying the history of municipal water inputs into central Texas watersheds. In the Waller Creek watershed, bald cypress trees were planted as saplings in 1928, 1936, and in the 1950s. We focus our study along the reach of Waller Creek that flows through the University of Texas campus and along two reaches of Onion Creek (Fig. 1). All trees studied are located on the creek bank or within 3 m of the bank, and all have major roots that extend into the creek. All Waller Creek trees studied are on the UT Austin campus (Fig. 1), within narrow riparian vegetation zones. None of these trees are directly irrigated. Their surrounding riparian zones are not currently irrigated, but 56% of the trees are adjacent to turf areas and may receive irrigation either (1) via some roots under turf areas or (2) by occasional accidental overspray. Onion Creek trees are in state or municipal parkland and none of the trees appear to have ever been irrigated. Thus, if municipal water from irrigation is taken up by these trees, then this likely occurs almost entirely via irrigation water contributing to streamflow.

Natural and social characteristics of the Waller and Onion Creek watersheds portray their characterization as urban and rural endmember watersheds, respectively (Table 1). Road density and impervious cover are two such delineating measures (Fig. 1 and Table 1, respectively). During storms, both creeks exhibit high energy and flooding, and Waller Creek has a flashier storm hydrograph, consistent with the high degree of impervious cover in its watershed. Geochemical results[14,17] and urbanization characteristics show that Waller Creek is the most urbanized and Onion Creek is among the least urbanized (rural) of seven Austin-area watersheds (Fig. 1 and Table 1). Geochemical variations in Sr isotopes ($^{87}Sr/^{86}Sr$) and fluoride between natural stream water and municipal water in seven Austin-area watersheds suggest significant inputs of water from the municipal infrastructure by leakage and irrigation into the natural streams—up to 90% of baseflow in some instances[14,17]. The inputs of municipal water scale with the degree of a watershed's urbanization, with Onion Creek at the low end and Waller Creek at the high end of this municipal water contribution. Consistent with this hypothesized input of municipal water, climate parameters (i.e., drought index) and streamflow exhibit weaker correlations in Waller Creek compared with Onion Creek (Supplementary Fig. 1).

Results

Chronologies

We develop a bald cypress tree-ring chronology ("dendrochronology") for multiple cores from multiple trees for the highly urbanized Waller Creek watershed and the minimally urbanized ("rural") Onion Creek watershed (Table 1). These are complemented by two control bald cypress chronologies previously developed from two rural watersheds (Krause Springs and Guadalupe River State Park), ~70 km to the west of our study area[25]. Together, these chronologies (or "ring-width index time series"; Fig. 2) provide a gradient from dominantly natural to extensively urbanized watersheds with which to evaluate the history of potential impacts of urbanization on watersheds. The younger age range for the Waller Creek cores (Fig. 2) is consistent with the periods of planting of these trees (1928, 1936, 1951)[31], whereas the Onion Creek trees are naturally growing and longer-lived.

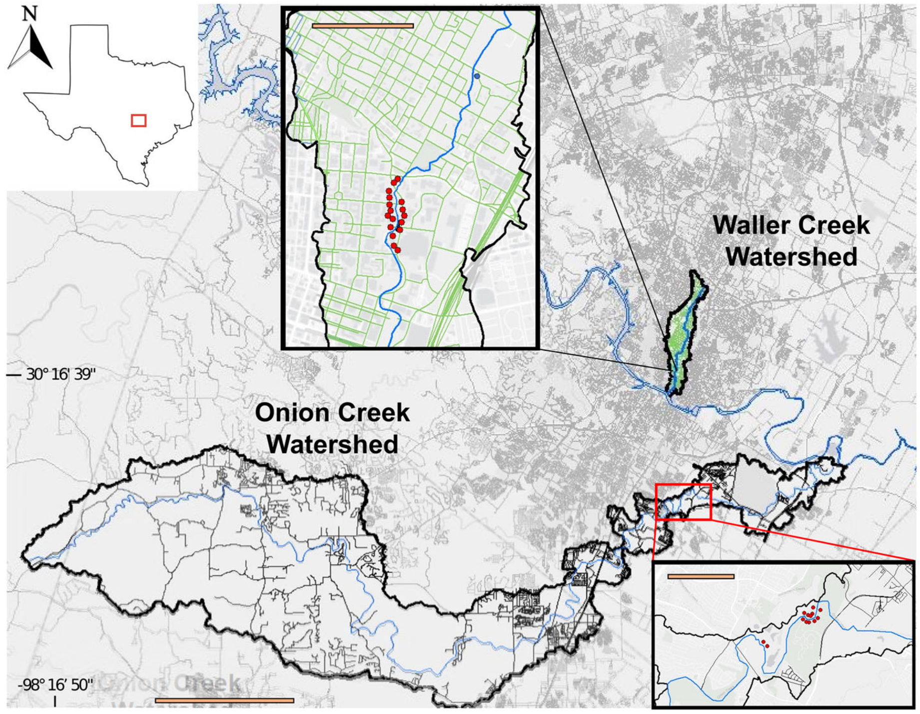

Fig. 1 | Waller Creek and Onion Creek watershed boundaries and road density map of Austin. Scale bar is 20 km. Expanded insets show the locations of tree core samples (red circles). Road densities and other measures (Table 1) are used to characterize Waller and Onion Creeks as the urban and rural endmember watersheds, respectively, in this region. Map after ref. 52, which uses watershed boundaries from ref. 53 and road data from ref. 54. Waller Creek inset scale bar is 1 km; Onion Creek inset scale bar is 2 km.

Table 1 | Hydrogeologic and urbanization characteristics of urban and rural watersheds studied

Imperv. cover[a,b] (%)	Pop. density[c] (persons/km^2)	Bedrock Unit[d]	Water quality[e]	Area (km^2)	# Trees[f]	Age range[g]	Diameter[h] (cm)
Waller Creek watershed							
61	2363	Austin Chalk	Marginal	15	21, 40, 34	1933–2017	108
Onion Creek watershed							
6.8	59	Glen Rose Fm., Edwards Limestone	Very Good	547	18, 28, 17	1844–2018	95

[a] Impervious cover percentages from the City of Austin (J. Collins, pers. comm., 2023).
[b]Major land use types are roads, driveways, and pavement (35% Waller, 4.7% Onion), buildings and structures (22% W, 1.5% O), and golf courses, pools, and sports fields (1.8% W; 0.29% O). Austin's water infrastructure for drinking and wastewater treatment was established over the period of 1871–1925[48,49], prior to the growth of the Waller Creek trees.
[c]Population density data from refs. 50,51
[d]Primary bedrock units listed; all are Lower Cretaceous marine limestone.
[e]City of Austin modes of Water Quality scores in Environmental Integrity Index Reports[51].
[f]Values refer to the number of bank-side trees as (# trees cored, # cores analyzed, # cores crossdated).
[g]Age range from tree core chronologies within the watershed.
[h]Median diameter (cm) at breast height of trees analyzed. Streamflow-climate parameter relationships presented in Suppl. Fig. 1a–c.

Onion Creek watershed (rural)

For Onion Creek, we collected 28 cores from 18 trees, with two cores from six of these trees, three cores from two of these trees, and one core each from the remainder. Of these cores, 17 could be crossdated, representing 13 different trees. Samples that could not be crossdated covered too short of a time interval, usually due to rot, or less commonly due to evidence of multiple locally absent rings. The longest measurement ring-width index time series ('time series' hereafter) dated to 1844, the average length was 131.9 years, and 2242 ring widths were measured with four locally absent (missing) rings discovered. Within each watershed's set of cores analyzed, we assess the extent to which the trees' time series correlate to each other (i.e., series intercorrelation). The Onion Creek time series yields a series intercorrelation, which is the mean correlation between each measurement time series and the average of all others, as calculated using COFECHA, of 0.510.

Waller Creek Watershed (urban)

For Waller Creek, 21 trees were sampled, all of which were cored twice except for two trees that were cored once, yielding a total of 40 cores. Covariability in growth patterns was weak within and among trees such that, even with extensive visual re-inspection, accurate crossdating could not be guaranteed for the Waller Creek trees. Indeed, within some individual trees growth patterns of multiple cores do not significantly agree with one another ($p > 0.05$). Cores from four trees had micro-rings and thus may have been prone to locally absent rings. Given that shared growth patterns were too weak to identify any locally absent rings through crossdating, cores from these four trees (eight cores) were excluded from further analysis, yielding 34 measured cores. At Waller Creek the oldest core dated to 1933, 2255 rings were measured, the average timeseries length was 66.3 years, and the series intercorrelation as calculated by COFECHA was $r = 0.223$.

Rural-urban watershed comparisons

In comparison with Onion Creek, growth patterns among samples from Waller Creek are much less coherent. Consistent with this, the amplitude of the Waller chronology is muted in comparison to the Onion chronology (Fig. 2 and Supplementary Fig. 2). This difference in the level of growth covariability is also reflected by the observation that the interseries

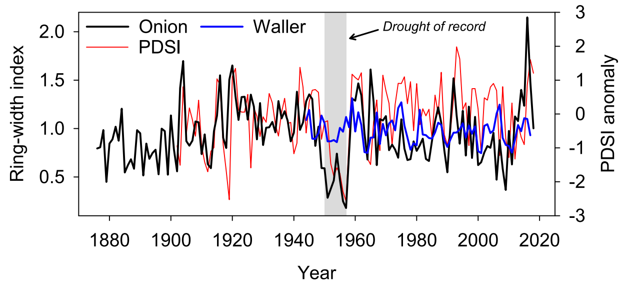

Fig. 2 | Onion Creek and Waller Creek bald cypress ring-width index chronologies. The mean value of these dimensionless ring-width indices is one. The 'Drought of Record' occurred from 1950–1957 and is used for water resource planning in Texas[3,55]. Also shown is the mean PDSI anomaly from prior-year November through current-year August[56]. Negative anomalies indicate drought conditions. Comparisons of Onion and Waller Creek chronologies with two rural chronologies to the west of the study area are given in Fig. 4.

correlation at Waller Creek is half the value of Onion Creek, even over the common interval of 1933–2017. Correlations with monthly-averaged drought are significant for both chronologies over their shared 1944–2017 interval (Fig. 3). Correlations are substantially weaker for Waller Creek and span a somewhat narrower seasonal window relative to Onion Creek (Figs. 2, 3a, b). Correlations in all cases are positive, as expected, given that negative PDSI values indicate dry conditions while positive values indicate wet conditions. Peak correlations for Waller Creek span approximately April through October (Fig. 3a), and the spatial extent of correlations averaged across this window spans most of Texas (Fig. 3b). The spatial correlations of Onion Creek against its seasonal window of peak correlation, spanning prior November through current August, are much higher (Fig. 3d), reflecting strong climate sensitivities. Consistent with these results, the rural Onion Creek chronology more closely tracks the "drought of record" of 1950 to 1957 (Fig. 2), as expected given the stronger PDSI correlation.

The Waller Creek and Onion Creek chronologies weakly correlate with one another ($r = 0.22$; $p = 0.07$), and over their common interval of 1944 through 2009, Waller Creek does not significantly ($p > 0.05$) correlate with previously published Krause Springs or Guadalupe River chronologies. The Onion Creek chronology does, however, correlate with both the Krause Springs ($r = 0.36$; $p = 0.003$) and Guadalupe River ($r = 0.38$; $p = 0.002$) chronologies over this common interval. Relationships are stable over time, remaining highly significant ($p < 0.001$) over the 1876–1943 interval at $r = 0.43$ for Krause and $r = 0.37$ for Guadalupe. Further, the Krause and Guadalupe interseries correlations are 0.516 and 0.530, respectively, consistent with Onion Creek (0.510) and in contrast to Waller (0.223). In a principal component analysis of the four chronologies over the shared 1944–2009 interval, axis 1 explains 47% of the variance and axis 2 explains an additional 22%, with loadings that separate Waller Creek from the other three chronologies (Fig. 4). This reflects the grouping of the three climate-sensitive rural sites[25] as distinct from the urban Waller Creek site.

Discussion

Key results for our Austin-area bald cypress tree-ring growth series are the contrasts between the trees in the rural Onion Creek vs. urban Waller Creek watersheds that include (1) a strong positive (weak) correlation with instrumental drought in the rural (urban) watershed, (2) strong positive (lack of) correlation between tree-ring growth chronologies in the rural (urban) watershed and other locations in the central Texas region, and (3) strong (absent) synchronous growth among tree-ring series within the rural (urban) watershed. We interpret these results in the context of understanding the role of urbanization in modifying natural hydrologic systems and the resilience of water resources that support ecosystems.

For the rural watershed, the strong intercorrelation in tree-to-tree time series in relative ring width, and significant coherence between ring width and drought-induced perturbations in water availability are all consistent with an external driver of growth. The other two rural watersheds (Krause and Guadalupe) show similar strong interseries correlations, indicating relatively strong growth covariablity within each of the three rural sites, which in turn is consistent with an external environmental driver. Evidence for such an external driver (such as climate) is much weaker for the urban watershed tree ring growth series (Figs. 2, 3). We interpret these outcomes as indicative of the existence or absence of inputs from the municipal water infrastructure (in urban vs. rural watersheds, respectively), the presence of which will transfer municipal water to natural streamflow. Waller Creek trees are surrounded by impervious cover and reside in a highly urbanized setting (Fig. 1). We expect correlations with climate to be low for tree-ring datasets that are not crossdated[32]. In tree-ring datasets in which there is synchrony (covariance) in growth among trees, failure to crossdate results in these signals canceling out one another as peaks are averaged with troughs across mis-aligned time series. However, Waller Creek tree cores have minimally synchronous patterns with which to crossdate, which indicates that these trees are not strongly limited by the environment, and thus would not be expected to correlate with climate. The oldest crossdated age of 1933 is essentially the same as the known age of transplanting (1936) plus an assumed sapling age of 3 years, supporting the accuracy of the Waller crossdating results.

Water from municipal infrastructure, via leakage and/or irrigation, can provide water year-round to riparian bald cypress trees, buffering them from the effects of water stress during even extended drought. Urban infrastructure failure and consequent leakage is evident in cities in general and Austin in particular, consistent with a significant input of municipal water into natural streams in Austin-area watersheds. Evidence for this leakage comes from studies of municipal infrastructure metering, physical hydrogeology, and streamwater geochemistry. Physical estimates of water lost from municipal infrastructure based on methods such as mass balance of inputs and outputs to the municipal network, range from 5% to over 60% for various cities of the world[15]. Typical losses in developed countries are 20–30%, and losses in Austin are estimated at 8%[15,33]. These central, city-wide estimates of the transmission of water from infrastructure to natural environments have significant uncertainties[16]. These estimates also do not provide information on individual watershed or point-source scales, and thus specific instances and/or sites of transmission from failing infrastructure commonly occur underground and go undetected. To address this lack of information, leak-detection technology and predictive models that are time and cost-intensive may be applied in some cases[34,35]. Novel applications of streamwater geochemistry can also provide watershed- and site-scale constraints[14,17].

The lack of growth synchrony within and among trees in the urban watershed may reflect, in the absence of an external climate driver, a significant component of water from Austin's municipal infrastructure in the urban Waller Creek. This interpretation is supported by our anecdotal observations of stormwater drains that have continuous flow into Waller Creek, including during extended periods of little to no rainfall. The Onion Creek trees reside in a largely rural watershed and demonstrate the expected high-amplitude growth variability associated with climate-driven water availability (Fig. 2 and Supplementary Fig. 2). The relatively smaller extent of municipal infrastructure upstream of the cored trees in Onion Creek is consistent with lower input of leaked supply and wastewater and/or irrigation into the natural system.

The lack of growth synchrony in the urban watershed under a relatively stable water supply via baseflow, may be due to tree-to-tree variability in other factors that affect tree ring growth. The most likely of these are competitive effects, especially crown access to light, but could also include physical damage, nutrient supply, soil properties, rooting structure, and sources and deposition of toxins at each site. Several factors relate to the observed coherence, or lack thereof, between climate and tree-ring growth rate between the urban and rural watersheds. These include the urban

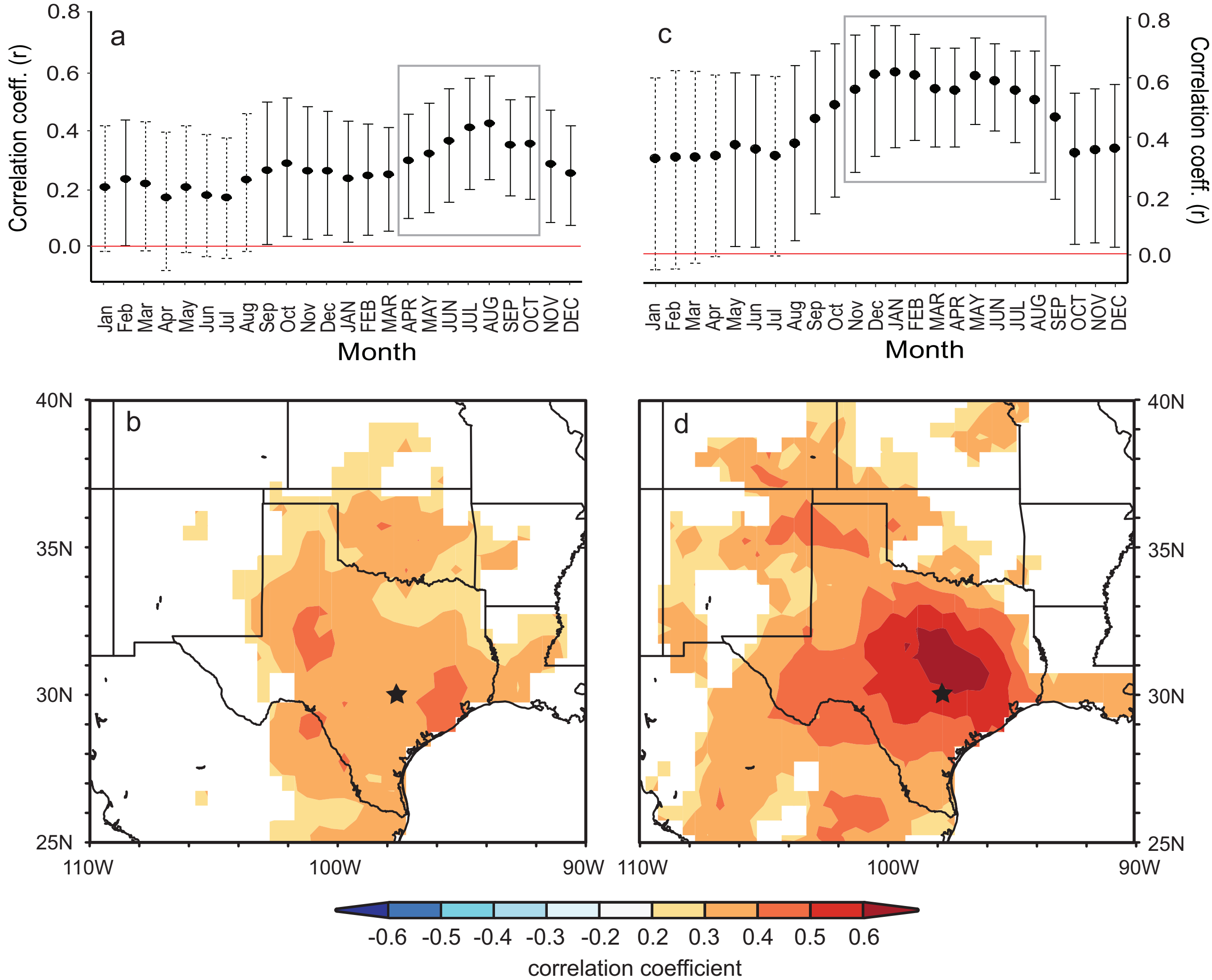

Fig. 3 | Relationships between time series of climate and bald cypress growth for the two watersheds over the common interval of growth of 1944–2015. Climate is expressed as monthly-averaged Palmer Drought Severity Index (PDSI) and bald cypress growth is expressed as ring-width anomaly (i.e., "chronology"). **a** Correlations between the Waller Creek chronology and monthly-averaged PDSI. The correlation between the Waller ring-width chronology and monthly-averaged PDSI[46] is for a given month (months in caps on x-axis) of each year for 1944–2015 and for each month of the prior year (months in lower case on x-axis). Correlations are shown with bootstrapped 99% confidence intervals; the red horizontal line is where correlation is zero. Gray box indicates the season for which correlations are strongest. **b** Correlations between the Waller Creek chronology and gridded PDSI as averaged over the season for which relationships with the Waller chronology are strongest (i.e., gray box in Panel a), which corresponds to April through October for a given year. **c** Correlations between the Onion Creek chronology and monthly-averaged PDSI is for a given month (months in caps on x-axis) of each year for 1944–2015 and each month of the prior year (months in lower case on x-axis). Correlations are shown with 99% bootstrapped confidence intervals; the red horizontal line is where the correlation is zero. **d** Correlations between the Onion Creek chronology and gridded PDSI as averaged over the season for which relationships with the Onion chronology are strongest (noted by the gray box in Panel **c**), which corresponds to prior November through current August for a given year. Black star is location of Austin, Texas.

watershed having the following: (1) a relatively uninterrupted water supply due to impaired or failing infrastructure and irrigation (Supplementary Fig. 1); (2) relatively high nutrient loading even during drought (e.g., Table 3 in refs. 3,17) a more managed landscape; and (4) extensive impermeable cover, creating high energy flow during rainfall events, which limits chances for other saplings to become established and thus limiting competition.

As outlined in the Introduction, there are four inputs of water to riparian bank-side bald cypress trees in the urban watershed. These are derived from (1) rainfall into the natural hydrologic system, (2) leaking municipal supply, (3) leaking municipal waste, and (4) intentional irrigation. Our study provides evidence for a component to streamflow from sources 2, 3, and/or 4. Delineating between these components will help inform watershed management to address water-resource resilience. In the urban Waller Creek watershed, the stand of bank-side bald cypress studied are not directly irrigated, but this does not preclude a contribution to streamflow from irrigation elsewhere in the watershed. In studies of managed, irrigated orchards in other regions, orchard growth is most strongly controlled by local factors, including irrigation and orchard maintenance rather than hydroclimatic conditions[36], whereas in other irrigated settings growth is clearly affected by hydroclimatic conditions, suggesting that the tree water demand was not fully satisfied by irrigation[37]. In the Waller Creek watershed, inputs 2 and 4 are the same source water, and therefore, water quality evidence in general cannot delineate between them. Water quality can be used, however, to trace the influence of municipal wastewater. Indeed, analysis of Waller Creek water samples over the past two decades indicates that there is a component of municipal wastewater in stream baseflow, based on the concentrations of wastewater indicators such as total coliform, *E. coli*, nitrate, and sulfate[14,17,38]. Results of modeling fluid mixing and water-rock interaction processes in Austin-area watersheds are used to estimate that a significant component of municipal water contributed to

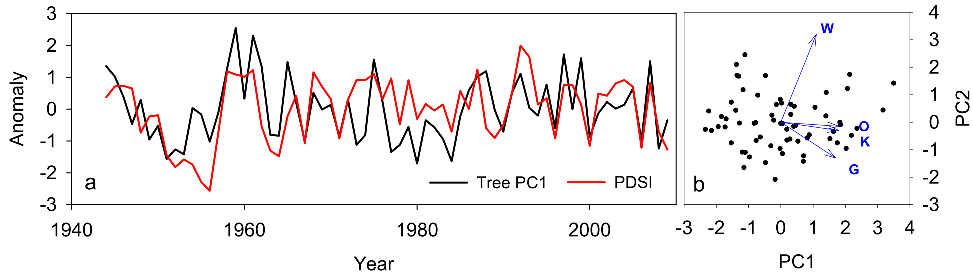

Fig. 4 | Principal component analysis of the four bald cypress chronologies: Onion Creek, Waller Creek, Krause Springs, and Guadalupe River State Park. **a** The leading principal component (PC1) of the four bald cypress chronologies PC1 captures 47% of the variability in the dataset and spans the common interval of 1944–2009. Also shown is the mean PDSI anomaly from prior November through current August, corresponding to the general seasonal window when correlations between bald cypress growth and PDSI tend to be strongest (as shown in Fig. 3). Both variables have been normalized to a mean of zero and standard deviation of one and correlate at $r = 0.52$; $p < 0.001$. **b** Biplot of the principal component analysis scores for principal components 1 and 2. Blue vectors are eigenvectors for Onion Creek (O), Krausse Springs (K), Guadalupe River (G), and Waller Creek (W).

stream baseflow (including Waller Creek) is wastewater (~25–50%)[14,17]. This indicates that irrigation alone cannot account for the increased Waller streamflow from anthropogenic sources (i.e., inputs 2–4 above).

Our results indicate that the influence of municipal water inputs to the natural hydrologic systems of the Waller Creek watershed has occurred over the period of record provided by the bald cypress trees, which have grown since the 1930s. The results also portray the potential for a positive, unintended consequence of urbanization in that urban tree growth appears to not have been as significantly affected by extended droughts as tree growth in rural watersheds in the region. The magnitude of the impacts of such positive consequences may well be small relative to those of the negative consequences comprising urban stream syndrome. Understanding the tradeoffs and feedbacks between these positive and negative effects on the resilience of stream water resources is of particular interest under 21st-century projections for increases in aridity and urbanization in the study region.

Implications and future research

As population growth fuels the expansion of urban centers in the 21st century, many watersheds will become increasingly urbanized, including through the build-out of municipal water supply and wastewater networks. To understand the history of and plan for the development of these networks in the most sustainable way, several new research directions should be undertaken, including (1) understanding how municipal infrastructure in the Austin, Texas area has failed over time by reconstructing infrastructure growth and the evolution of stream water quality over the past century; (2) understanding how municipal treated supply and wastewater geochemically evolve after they are transferred into the natural hydrologic system; and (3) model/design municipal water networks and policies to minimize and monitor failure and allow for deliberate/controlled transfer from the network to the natural stream, to help mitigate against impacts from climate change and social inequities[39]. With further development of the transfer functions between stream water chemistry and tree-ring chemistry, we can potentially reconstruct when and how infrastructure failure engendered the transfer of municipal water to natural streams, which can lead to decoupling between climate change and riparian ecosystem function.

The results of this study demonstrate that riparian bald cypress tree-ring chronologies have the potential as proxies for temporal changes in the anthropogenic influence of urban infrastructure on natural systems. We leverage well-understood relationships between tree ring growth and climate conditions at multiple rural sites and one urban site to demonstrate that trees in the extensively urbanized watershed are decoupled from some climate variability, such as drought. We infer that this decoupling is due to contributions from the municipal water network that sustains baseflow during drought conditions. Such a proxy is readily applicable to urban locales with bald cypress or other well-understood, streamflow-sensitive trees in urbanized riparian zones.

Methods

Coring and imaging

We collected cores at breast height from 21 trees in Waller Creek in June 2018, and 18 trees in Onion Creek in June 2019, using 32-inch and 39-inch increment borers. The trees are dominant or codominant. At least two cores were collected from most trees, though in some cases, only a single core could be analyzed due to intermittent periods of wood decay. Cores were taken parallel to any topographic contours to avoid reaction wood (i.e., wood produced as a response to stem lean), and where possible, ninety degrees apart across the tree bole. Cores were dried, glued to wooden blocks, and then surfaced with increasingly fine sandpaper to 400 grit, followed by final polishing with 30-micron and occasionally 15-micron lapping film. Next, we visually crossdated all cores, first within each tree and then within each site[40]. Cores were then imaged on an Epson Expression 12000XL scanner at 2400 or 3200 dpi resolution. Many samples were of sufficient length that they required multiple overlapping scans, which were merged into a single mosaic using the "Photomerge" function in Adobe Photoshop software.

Ring measurement and crossdating

Total ring width was measured to the nearest 0.01 mm using CooRecorder software[41]. Once all measurement time series had been completed, a final statistical check of crossdating was performed using the program COFECHA[42]. In COFECHA, each measurement time series was detrended with a cubic spline of 50% frequency cutoff at 32 years to isolate the high-frequency component of growth. To ensure serial independence and thus meet assumptions of correlation analysis, any remaining autocorrelation was removed using low-order autoregressive functions[42]. Each standardized time series was correlated to the mean of all others in 50-year segments overlapping by 25 years. Using this approach, any dating errors would frameshift (i.e., temporally offset) the growth pattern in time, causing a conspicuously low correlation in segments that pre-date the error. The wood of any samples with low correlations was visually re-inspected and measurements corrected if an error was identified.

Chronology-climate correlations

Each measurement time series was standardized using modified negative exponential functions to remove tree age- and size-related trends. These standardized measurement time series were averaged into site-level chronologies using a biweight robust mean to reduce the influence of outliers. All chronology construction was performed using the program ARSTAN[43]. We calculated correlations between each bald cypress chronology and monthly-averaged Palmer Drought Severity Index (PDSI) over a 24-month period spanning January of the year prior to ring formation through December of the current year using the R package TreeClim[44]. Significance ($p < 0.01$) was calculated via bootstrapping using methods adapted from DENDROCLIM2002[45]. Drought data used were one-degree gridded self-calibrating PDSI averaged over the region 95°W to 100°W longitude and 28°N to 32°N latitude[46]. The chronologies were also correlated against the gridded PDSI using the KNMI Climate Explorer to illustrate the spatial distributions of climate relationships[47].

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

All tree ring measurements are provided in the Supplementary Tables 1, 2.

Received: 14 February 2023; Accepted: 9 February 2024;
Published online: 20 March 2024

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Acknowledgements

This research was supported by the following NSF programs: Hydrologic Sciences (EAR 2055536), Coupled Natural and Human Systems (AGS 1518451), Cultural Transformation of the Geoscience Community (RISE 2228205) and Research Experiences for Undergraduates (EAR 1560451). We also acknowledge the support of the Cynthia and George Mitchell Foundation (G-1809–55892), and the F.M. Bullard Professorship of the Jackson School of Geosciences, the Environmental Science Institute, and the Planet Texas 2050 initiative at The University of Texas at Austin. We thank Josiah Sananda, Rosemary Burkhalter-Castro, Lakin Beal, Hunter Manlove, Julia Holland, Alessandro Mauceri, Anna Loewald, Swara Mukkamala, and Nayoung Hur for their assistance in the field and the lab; the UT Urban Forester, the City of Austin Parks and Recreation Department, and Texas Parks and Wildlife Department for assistance with acquiring permits, access, and logistical support; and Josiah Sananda, Jennifer Hrobar, Kasey Faust, Jose Abella, and MaryLynn Musgrove for constructive discussions.

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J.L.B.: Project conception, project design, field sampling, data interpretation, manuscript drafting; B.A.B.: project design, field sampling, crossdating, statistical analyses, data interpretation, manuscript editing; D.M.T.: field sampling, data interpretation, manuscript editing. All authors approved the final version.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s42949-024-00144-1.

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