Increasing summer river discharge in southern California, USA, linked to urbanization

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[1] Semi-arid southern California relies heavily on imported water for domestic use. A synthesis of river discharge data in this region reveals that summer (June, July, and August) river discharge in watersheds that have at least 50% urban, suburban, and/or commercial land cover has increased by 250% or more over the past half-century, without any substantial precipitation during these months. Total annual discharge in the Los Angeles River has also increased at levels up to several hundred percent. Three factors likely contribute to our observations: (1) increased groundwater recharge rates from leaking water pipelines, (2) inputs of treated wastewater into streams and rivers, and (3) increased runoff or recharge due to over-irrigation of ornamental landscaping. In the southwestern United States, water importation consumes large amounts of energy and contributes to decline of river flows in source regions. Here we show that water importation also increases river flows in urban areas. **Citation:** Townsend-Small, A., D. E. Pataki, H. Liu, Z. Li, Q. Wu, and B. Thomas (2013), Increasing summer river discharge in southern California, USA, linked to urbanization, *Geophys. Res. Lett.*, *40*, 4643–4647, doi:10.1002/grl.50921.

1. Introduction

[2] Water resources in arid regions are often supplemented by imported water. In coastal southern California, home to ~40 million residents, scarce water resources are supplemented by large volumes (~1.6 billion m^3 annually) of imported water from the San Joaquin-Sacramento River delta, the Colorado River, and Owens Valley, leading to declines in fish stocks and river flows in source regions [*Elmore et al*., 2003; *Zektser et al*., 2005; *Kimmerer*, 2008]. Previous studies of urbanized watersheds have shown that urbanization can increase wet-season stream discharge due to an increased runoff to infiltration ratio caused by impervious surface cover [*Paul and Meyer*, 2001; *Pickett et al*., 2011]. However, in arid and semi-arid cities, rainfall may only occur during a handful of days per year, and irrigation may be a larger driver of groundwater recharge and surface flow than rainfall [*Roach et al*., 2008; *Jones et al*., 2012]. Previous studies have already shown that irrigation drives accelerated hydrologic cycling in semi-arid agricultural systems, including groundwater depletion and increased evaporation, precipitation, and river discharge [e.g., *Lo and Famiglietti*, 2013].

[3] Despite reduced infiltration rates due to impervious surface cover, total groundwater recharge rates can increase with urbanization, particularly in semi-arid and arid regions [*Lerner*, 1990, 2002; *Howard*, 2002; *Garcia-Fresca and Sharp*, 2005; *Hibbs and Sharp*, 2012]. Underground water infrastructure almost always leaks, at rates probably around 10% or 20% or higher [*Lerner*, 1986, 1990, 2002], leading to increased groundwater recharge. For example, in Lima, Peru, anthropogenic recharge is approximately 2.5 times natural recharge due to leaking water conveyance pipes and irrigation of landscaping [*Lerner*, 1986, 1990]. Water importation combined with leaking water supply systems and sewers have raised groundwater tables in urban areas in Ukraine, leading to severe under flooding and resulting in landslides, subsidence, and karst development [*Jakovljev et al*., 2002].

[4] In order to link this previous knowledge of the impact of urbanization on groundwater in semi-arid regions with surface water hydrology, we used stream gauge data from the United States Geological Survey as well as observations of land use from satellites to determine how stream flow has changed as urbanization has increased over the past century in southern California, USA.

2. Methods

[5] In order to quantify changes in stream discharge, we used the U.S. Geological Survey (USGS) real-time water database for southern California, USA. We selected coastal streams in Los Angeles, Orange, and San Diego counties (Figure 1), excluding those sites with impoundments or diversions or with only a short-term record. For each stream gauge station, we determined its upstream watershed boundary with USGS 30 m resolution digital elevation models (DEMs) and hydrological analysis routines in the ArcGIS geographic information systems software package. Land use and land cover types within the upstream watersheds of gauge stations were determined by overlaying the upstream watershed boundaries with the 2001 National Land Cover Database, which were derived from 30 m resolution Landsat multispectral imagery. The percent of undeveloped, low intensity residential, high intensity residential, commercial/industrial/transportation, and agricultural land use are calculated and summarized for each gauge station's upstream watershed in Table S1 in the supporting information. Clearly, these stream watersheds have a range of land cover types. Some stream watersheds are nearly completely undeveloped, and others are more than 50% developed.

Additional supporting information may be found in the online version of this article.

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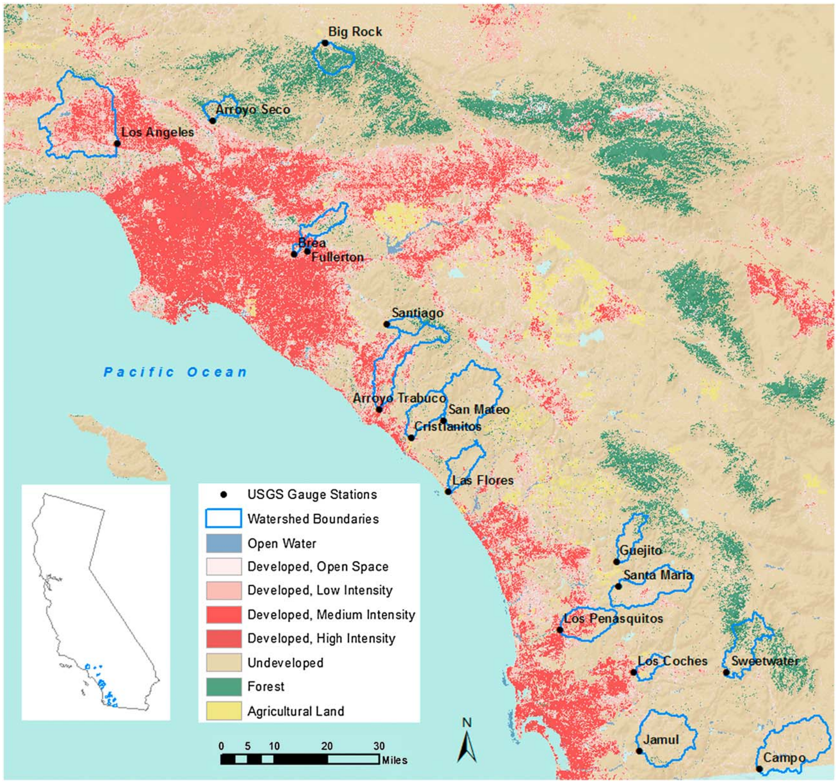

Figure 1. Map of the study area, including selected watersheds outlined in blue. Land cover data (see legend) are derived from the National Land Cover Database 2001 data set. Inset shows location in California, USA.

[6] For the current study, the summer season is defined as June, July, and August. These are typically the driest months in southern California and, in most years, no precipitation is recorded. No change in summer precipitation has been observed at the National Weather Service station in downtown Los Angeles, California (Los Angeles Civic Center station) through the period of record (1906 to 2012) (http://www.nws.noaa.gov/climate/local_data.php?wfo=lox). The average summer precipitation for the period of record is approximately 3 mm.

[7] To determine whether summer river discharge has changed, we combined daily river discharge estimates for summer in each year of the record. Each summer discharge total (Q) was compared to a midcentury baseline for the same river. In general, this was 1950–1960, but for some rivers, the gauge was not operating during all of those years, or the river discharge was zero during this time period. The specific reference period for each river in the study is shown in Table S1. We then calculated linear regressions of change in Q versus year for the entire period of record for each river. Values of p for the regression trend significance test are shown in Table S1. P values less than 0.05 were considered significant changes; the slope of this regression line (% change in Q per year) for significant relationships is also shown in Table S1. We also compiled summer runoff totals for each river (Figure 2), using the watershed area given by the USGS and shown in Table S1.

3. Results and Discussion

[8] Urbanized watersheds have experienced large increases in summer river discharge in the past century while stream discharge in undisturbed areas has generally not changed (Figure 2). Of the undeveloped watersheds, only Las Flores River had a positive increase in summer river discharge over the study period (361.5% per year; Table S1 and Figure 2b). Summer river discharge significantly decreased in one undeveloped watershed, Jamul Creek (Table S1 and Figure 2a), at about 2% per year. In contrast, summer discharge increased in four of the six urbanized watersheds we analyzed (Figure 2c), at an average rate of between 5.7% and 43.5% per year (Table S1). In many urbanized streams, summer river discharge in the early parts of the record was near zero, with the exception of a few years of high flow in the midcentury.

[9] We also compared summer Q in the urbanized rivers from 2000 to 2010 relative to the baseline period for each stream (as defined in Table S1). Of these six rivers, four had significantly higher average summer river discharge in the last decade relative to the baseline period (Figure 3). The percent increase ranged from 265% (Los Penasquitos) to 1867% (Brea River) (Figure 3). Los Coches Creek and Arroyo Trabuco changed by 90% and 144%, respectively, but Q was not significantly different in 2000–2010 relative to the baseline period (Figure 3).

[10] Because there is nearly no atmospheric precipitation in the summer months, and because we have observed that increasing summer river discharge is more prevalent in urbanized watersheds than undeveloped watersheds, we conclude that anthropogenic inputs of water are the likely cause of increasing stream discharge in southern California. Indeed, a previous analysis of water balance in Los Angeles County found that the total volume of imported water and precipitation versus water losses via wastewater treatment plant outfalls was out of balance, such that over 60% of imported water had an unknown fate [*Ngo and Pataki*, 2008]. Increased water table

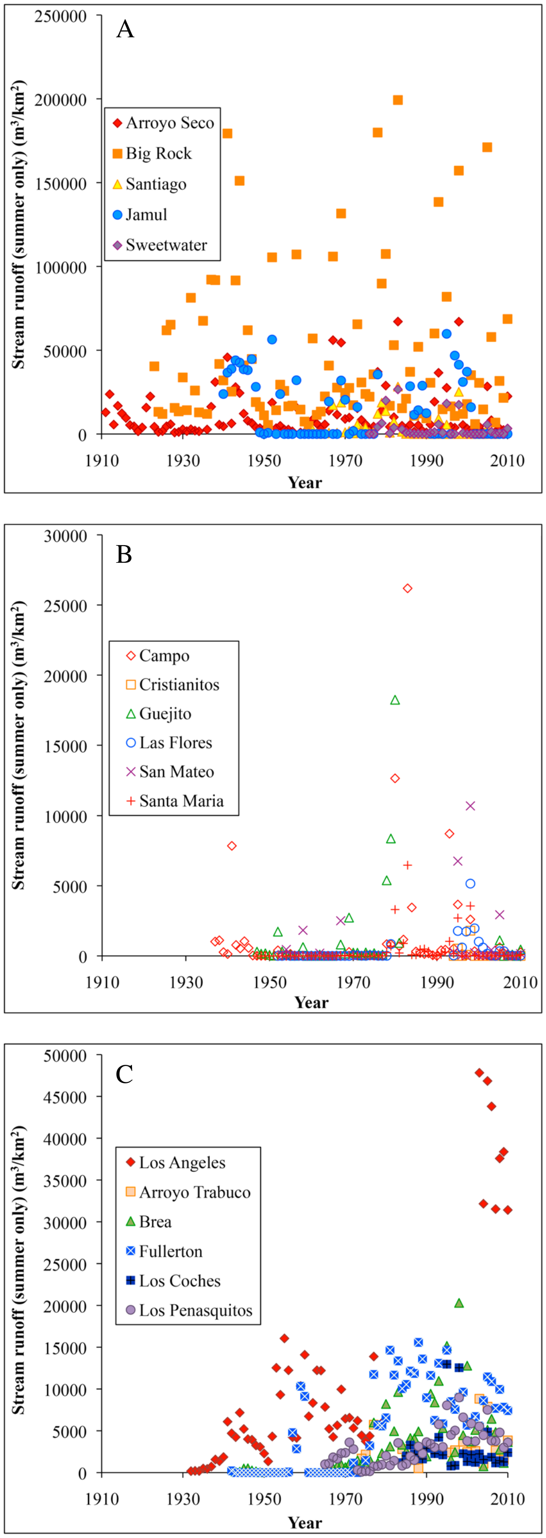

Figure 2. Change in summer (June + July + August) river discharge (m^3) relative to watershed surface area (km^2) (Table S1) for (a and b) watersheds greater than 80% undeveloped and (c) watersheds greater than 50% developed.

elevations due to enhanced recharge in urban areas is likely in this region, and at least one previous study in southern California has attributed increased dry-season streamflow to stream channelization and increased groundwater levels [*Hibbs et al.*, 2012]. In addition to this, treated wastewater and runoff and/or recharge of irrigation water also likely enhance summer stream flow in southern California.

[11] Treated wastewater supplements river flow throughout the developed world, and this input is particularly obvious in arid and semi-arid regions [*Paul and Meyer*, 2001]. The Las Flores River (Figure 2b) is one example of this: this watershed is located in the protected Marine Corps Base Camp Pendleton, with very low levels of land development (Table S1). However, for many years, this stream was used to dispose of treated wastewater, clearly reflected in summer river discharge data. It is very likely that urban streams in southern California also have large wastewater components of base flow. Of the 11 wastewater treatment plants in Los Angeles County, 10 are "water reclamation plants," which provide recycled water for groundwater recharge or to supplement irrigation resources. This process is also popular in Orange and San Diego Counties. Treated wastewater is the primary source of water (and nitrogen and phosphorus) in the South Platte River downstream of the Denver area during dry conditions [*Dennehy et al.*, 1998]. In Austin, Texas (a similarly semi-arid city), urban streams have an increased proportion of source water from the domestic water supply, compared to nonurbanized streams where groundwater is the predominant water source [*Christian et al.*, 2011]. Wastewater contributions to stream flow may also increase the threat of microbial or chemical contamination [*Wong et al.*, 2012], export of pharmaceuticals and personal care products [*Kolpin et al.*, 2004], and contribute to greater export of aged organic C in urbanized rivers [*Griffith et al.*, 2009]. Wastewater treatment plants in California also practice managed aquifer recharge, where treated wastewater is allowed to infiltrate to groundwater to supplement local water resources and prevent saltwater intrusion. In Los Angeles County, this practice contributes about 55 million m^3 of recycled water per

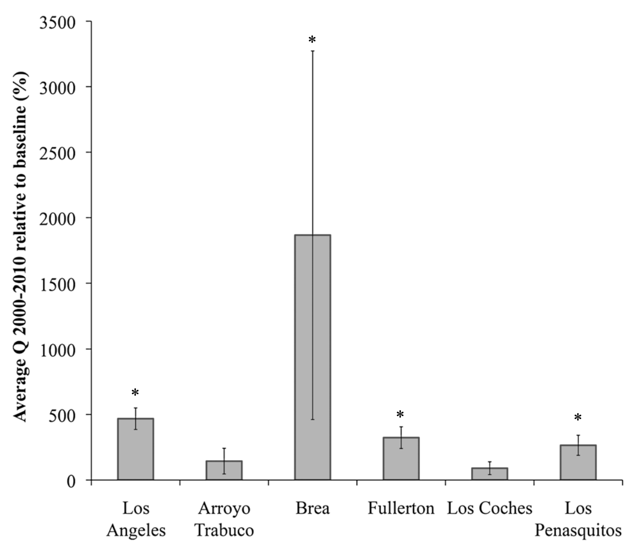

Figure 3. Average percent change in summer river discharge in urbanized watersheds in 2000–2010 relative to the midcentury baseline (baseline years listed in Table S1). The asterisk denotes the significant change since baseline period.

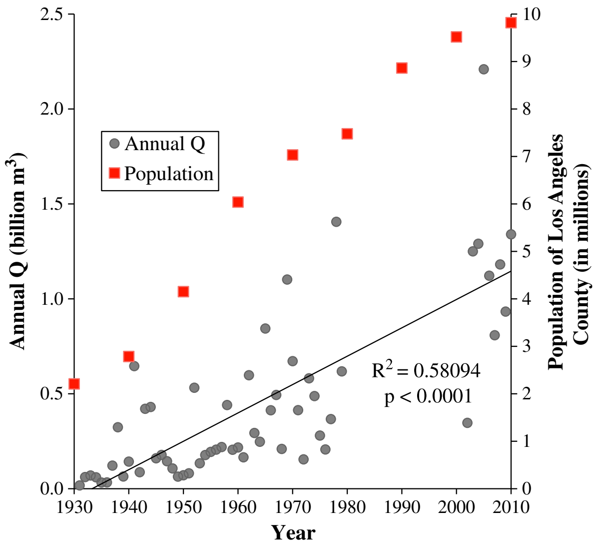

Figure 4. Total annual river discharge in the Los Angeles River at USGS gauge 11902450 from 1932 to 2010 (the gauge was inactive from 1980 to 2003). Also included are population estimates for Los Angeles County from the United States Census Bureau.

year to groundwater [*Johnson*, 2009], which likely contributes to increased stream flow rates in summer.

[12] The observed increase in summer stream discharge may also be due to increased runoff and recharge of irrigation water. This region has very low agricultural land cover (Figure 1 and Table S1), so irrigation is largely used for ornamental landscaping. Irrigation is the primary source of water to most urban vegetation in southern California [*Bijoor et al.*, 2012], resulting in increased rates of evapotranspiration [*McCarthy et al*., 2011]. Sap flux sensor measurements in Los Angeles have indicated that transpiration rates can approach 2 mm per day at the plot level in densely forested irrigated areas, such as parks [*Pataki et al*., 2011]. A further study of urban lawns showed that the largest loss of water from irrigated lawns was from infiltration, ranging from 40% to 65% of applied irrigation water [*Bijoor*, 2010]. Conceivably, much of this infiltrated irrigation water is transported through groundwater to small headwaters and storm drains. Landscaping irrigation has been linked to increased groundwater recharge in other arid cities, such as Riyadh, Saudia Arabia [*Rushton and Alothman*, 1994], Lethbridge, Alberta [*Berg et al*., 1996], and Austin, Texas [*Passarello et al*., 2012].

[13] Total annual river discharge has also increased in the Los Angeles River over the period of record ($p < 0.0001$) (Figure 4), likely due to a combination of increased precipitation-derived runoff during winter due to impervious surface area, as well as steady supplementation of stream flow with leakage from pipes, wastewater treatment plant effluent, and irrigation water. Much of the riverbed is channelized and paved with concrete, reducing contact between the river and groundwater for both discharge of groundwater to the streambed and recharge of groundwater from the stream. Over the past ~80 years, population in Los Angeles County has also steadily increased, from 2.2 million in 1930 to nearly 10 million in 2010 (U.S. Decennial Census, 1930–2010) (Figure 4). On average, annual river discharge was approximately 500% higher in 2000–2010 relative to 1950–1960, corresponding to an excess river discharge of over 90 million m^3 per year in recent years. This translates to ~6% of annual water imports lost in the Los Angeles River alone. A previous study of the fate of imported water in Los Angeles County estimated that about 4% of imported water is lost in rivers [*Ngo and Pataki*, 2008]. Our findings imply that this figure may be larger if annual river discharge has similarly increased throughout the region. Our calculation also does not account for the portion of imported water that is lost via offshore wastewater outfalls, which accounts for ~40% of water imports [*Ngo and Pataki*, 2008].

[14] This study demonstrates the need for long-term monitoring of stream flow in urban as well as remote areas. The implications of this study are broad: other arid cities, in the American West and beyond, are likely experiencing increased stream flows, and preliminary evidence indicates this is true in cities such as Austin [*Christian et al*., 2011], Denver [*Dennehy et al*., 1998], Phoenix [*Roach et al*., 2008], and Riyadh [*Rushton and Alothman*, 1994]. Such cross-watershed transport of water for urban use reduces water availability in source regions. In some regions, the increased loss of freshwater to the ocean and the atmosphere will be balanced by increased global evaporation rates and corresponding increases in precipitation [e.g., *Lo and Famiglietti*, 2013], but most regional climate models indicate that precipitation and snow accumulation rates are likely to decline in the southwestern United States [*Christensen et al*., 2007], with potentially catastrophic impacts on water resources [*Barnett et al*., 2008].

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