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Effects of Stormwater Capture and Use on Urban Streamflows

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Abstract

Cities across the globe manage stormwater to enhance water supplies. Capturing and using stormwater in urban watersheds can have benefits for groundwater recharge, reduced pollutant loading in downstream watersheds, and habitat management. In California, metropolitan areas in the southern coastal regions of the state have for decades captured an average of 493 Million Cubic Meters (400,000 acre-feet) of runoff annually to recharge groundwater. But in a state with highly managed watersheds and seasonal precipitation, capturing stormwater for water supply goals can affect urban streamflows. Using a model with simulation and optimization of regional urban water resources management in Los Angeles County (*Artes*), we analyze the potential effects of increasing stormwater capture and infiltration on urban streamflow volumes. Results indicate that for many watersheds in LA, further increasing stormwater capture and use would significantly reduce urban streamflow volumes, especially in downstream basins. But in some basins, streamflows are increased to preferentially direct water to existing stormwater capture basins. Results illustrate potential tradeoffs in water supply, in-stream water flows, and aquatic habitat that must be considered when looking to increase use of local water sources through more stormwater capture.

Keywords Stormwater capture · Runoff · Los Angeles · California · Hydrologic modeling · Optimization

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1 Introduction

Urban development affects natural watershed processes. It alters the timing and velocity of runoff (Hollis 1975; McCuen 1979). Increased pavement and impervious surface cover in cities is generally correlated with higher velocities of runoff and increased concentrations of contaminants (Leopold 1968; Dietz and Clausen 2008). The combination of imperviousness and imported water from out-of-basin sources can even increase local water tables and seasonal streamflow regimes (Melosi 2001; Gelo and Howard 2002; Manago and Hogue 2017). Distributed stormwater control measures, alternatively called Low-Impact Development (LID), green infrastructure, and others, are an increasingly popular design approach for mitigating the effects of urban stormwater runoff. Such devices, inserted throughout cities at small- to large-scales, can mitigate pollutants by capturing, treating, and sometimes infiltrating runoff before it reaches water bodies, while also reducing the peak flows from some storms that create downstream hydromodification effects such as incised channels (Low Impact Development Center 2000; Dietz 2007; EPA 2008; Center for Watershed Protection 2011). Additionally, capturing and infiltrating stormwater can help recharge groundwater aquifers. In urban areas reliant on groundwater as a source of water supply, such capture and use of stormwater, whereby runoff is intentionally retained in opportune areas for gradual infiltration, has been used for decades to improve the reliability of local water supply sources (Blomquist 1992; Brandt 2015; USBR and LACDPW 2016; Porse et al. 2017). Stormwater can even be used to augment water flows in altered basins (Halaburka et al. 2013).

But intentionally capturing stormwater can also have detrimental effects. Drainage infrastructure itself alters runoff patterns, which can reduce base flow (Walsh et al. 2012). Capturing more stormwater to improve water quality and even groundwater recharge may affect streamflow volumes that provide important recreational, amenity, water supply, and aquatic habitat uses. Identifying environmental flow requirements for urbanized catchments ensures sufficient streamflows that support important species (Rogowski et al. 2015; Stein et al. 2017, 2018). Systems analysis is a useful tool to inform management options that support environmental streamflows in arid watersheds (Tisdell 2010; Porse et al. 2015).

This technical note presents an analysis of potential tradeoffs when optimizing urban runoff management in Los Angeles County to support groundwater recharge for water supply. Namely, the analysis examines the effects that optimizing stormwater capture for groundwater recharge would have on local streamflow volumes that support environmental flows, habitat, and recreation. Using a simulation-optimization framework and comparing results to historic data, the analysis helps illuminate tradeoffs and unintended consequences of contemporary best practices for water management in a semi-arid urbanized basin. The research is novel by addressing a gap in literature to understand potential unintended consequences of implementing contemporary sustainable urban water management policies, in this case stormwater capture and recharge.

2 Methods

For the analysis, we used a previously published model of urban water resources management in Los Angeles (LA) County. The model, *Artes*, uses linear programming and a link-node network structure to simulate and optimize management decisions, with the goal of assessing the potential for local water supplies in LA and associated tradeoffs (Porse et al. 2017). For modeling stormwater, the model simulates a network of 25 stormwater capture basins (spreading grounds) that are located throughout LA County (Fig. 1). The basins vary in size and location, which capture and infiltrate an average of 246 Million Cubic Meters (200,000 acre-feet) of runoff annually.

2.1 Study Region

The model has been previously described in depth, so only important aspects of its development and performance relevant to this analysis are highlighted here (further details are included in the Supplemental Data). The *Artes* network includes over 100 water management institutions, natural features such as groundwater basins and the stream network, and engineered infrastructure including wastewater treatment and reuse plants, groundwater recharge spreading basins, and dams in the Los Angeles metropolitan area. The model covers 9 million people and 85 distinct cities, along with additional unincorporated areas. The link-node structure delineates existing linkages between network components, such as specified allocations among water importer, wholesaler, and retailer agencies, groundwater pumping rights of specific parties, and storage and flow constraints for infrastructure.

The Los Angeles metropolitan region is highly urbanized. It includes five large watersheds, with runoff collecting from the surrounding Santa Monica and San Gabriel mountain ranges and draining through a network of channelized rivers across the coastal plain towards the Pacific Ocean (Fig. 1). The region's hydrology is highly seasonal, with a handful of storms between November and March comprising nearly all of the annual precipitation. But while the coastal plain receives 254-380 mm (10-15 in.) of rainfall annually, much more (up to 1000 mm) can fall in the surrounding mountains at higher altitude. Beneath the surface, a vast network of interconnected groundwater basins contain, by rough estimate, over 50,000 MCM (nearly 42 million acre-feet) of total capacity, with annual allowable pumping allocations set at 780 MCM (633,000 acre-feet). Groundwater basins have been intensely managed and recharged for decades as a critical part of the region's water resources.

2.2 Approach and Formulation

Several versions of the model have been employed to study aspects of water planning in LA. First, a maximization framework was used previously to assess the *potential* for local water supplies in LA County across varying scenarios of imported water supply and demand. This

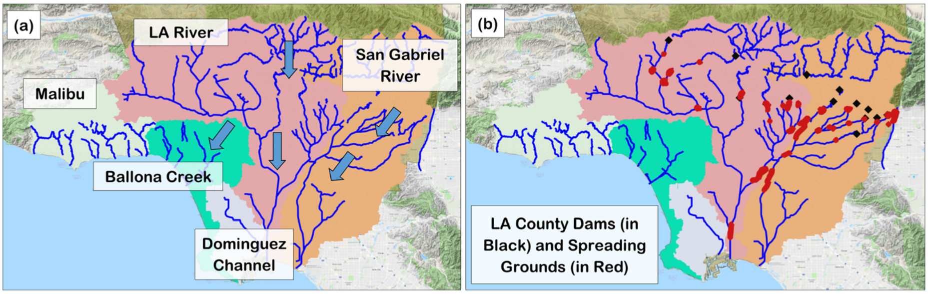

Fig. 1 Watershed flows and stormwater capture infrastructure in LA County. (a) Major watersheds of LA County included in *Artes*. (b) Locations of stormwater spreading grounds and flood control dams, which are jointly managed to increase groundwater recharge

included both global and limited optimization approaches, whereby global optimization (or "perfect foresight") optimizes across the entire time series and limited optimization only optimizes over a short time period (1 year in model runs to date with limited foresight). The objective function for this formulation maximizes flows (supplies) from local sources, including groundwater, spreading basins, and recycled water, to minimize shortages in relation to specified demands for each water agency. Specifically, the model objective function (Eq. 1) maximizes the sum (Z) of the difference between flows from local sources (Q_a) and shortages (S) across all retailers, such that:

$$Max\ Z = Q_a - cS \tag{1}$$

where, c is an arbitrary constant used to relate flow and shortages. Local supply sources are represented mathematically as flows where i is in the set of local source nodes:

$$Q_a = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} \left(Q_{ijk}\right) when\ i \in \{Local\ Sources\} \tag{2}$$

Second, a cost-minimizing formulation was used to assess economic effects of imported water reductions. For this formulation, the objective function (Eq. 3) is the difference between total costs (supply and distribution costs and assessed economic losses from residential outdoor water conservation) and assessed benefits, which were limited to recreational benefits associated with large stormwater capture basins (Porse et al. 2018):

$$Min\ Z = (C + D) - B \tag{3}$$

Total costs and damages depend on the flows of water across links in the system, each of which have associated cost coefficients. For supply costs, the sum (Eq. 4) is equal to the product of the volume of flow across link k (Q_{ijk}) and the specified unit cost of flows across link k (c_{ijk}):

$$C = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} c_{ijk} Q_{ijk} \tag{4}$$

Economic losses (Eq. 5) for residential water conservation are similarly calculated by summing the product of flow volume of reduced deliveries (S_j) to node j, and the unit cost associated with assessed economic losses for node j (d_j):

$$D = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} d_j S_{ijk} \tag{5}$$

Economic benefits B (Eq. 6) associated with certain stormwater capture uses are calculated across all nodes as the product of the flows and the unit value of benefits for that node:

$$B = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} b_j Q_{ijk} \tag{6}$$

In the flow maximizing scenarios reported here, the currently existing system is modeled. In the cost minimizing scenarios, some additional capacity is included in water reuse and stormwater capture facilities based on improvements being planned or investigated by agencies, as noted in regional reports. The remainder of the formulations are detailed in previous publications and summarized in this article's Supplemental Data section.

In both formulations, the singular decision variable in *Artes* is flow (*Q*) between nodes *i* and *j* over link *k* in the network. The model operates at a monthly time step (either 15 or 25 years) that corresponds with data availability for the LA system. The monthly temporal resolution results in some inconsistencies with likely real-world outcomes, such as potentially overestimating the volume of stormwater capture in some formulations (flow maximization) as compared to a model with higher temporal resolution that better estimates potential runoff capture for storms of hourly or daily duration in LA. This and other model limitations are noted previously (Porse et al. 2017).

2.3 Hydrology in Artes

Surface hydrology and flows, including precipitation inputs and losses to evaporation, evapotranspiration, and infiltration, were incorporated in *Artes* using the Watershed Management Modeling System (WMMS) developed by the Los Angeles County Department of Public Works (LACDPW and Tetra Tech 2009). WMMS is a continuous simulation model of hydrology and hydraulics in LA County. It simulates flows and water quality outputs, calibrated to gauge data, for a 25-year time frame at the hourly time step (1986-2010) for 2600 delineated sub-watersheds in LA County. Approximately 2200 of the watersheds were included in *Artes,* aggregated into 47 watershed zones. The watershed zones in *Artes*, which subdivide the major river watersheds of the county, correspond with the contributing upstream catchments of key system features such as spreading basins and surface water junctions. Hydrologic parameters for each watershed zone, including precipitation and losses to evaporation and groundwater infiltration, were derived from WMMS. The aggregated values of precipitation, watershed inflows and outflows, and evaporation losses in each watershed zone in *Artes* for the unaltered system serve as flow constraints within the optimization. WMMS is built with the Loading Simulation Program in C++ (LSPC) and the Hydrologic Simulation Program-Fortran (HSPF).

2.4 Model Calibration

Developing the model required a multi-step calibration process to govern the optimization procedure. First, water distribution system losses, including leakage, evaporation, evapotranspiration, and irrigation, were assessed and each retailer was assigned a loss rate based on an assessment of system inputs and outputs, including actual flow data for wastewater treatment plants. The loss rate was added as a constraint to simulate real system losses. Second, the validity of using WMMS for flow routing was verified. With the exception of stormwater capture basins, WMMS models the unaltered (though in some places hardened) water drainage network in LA. The full drainage network, however, includes many connections between natural and engineered features (see Supplemental Data section). Its usefulness as part of simulating the entire system had to be validated. Through this step, it was noted that adding wastewater treatment plant outflows that discharge into surface streams, which are not modeled in WMMS, increased the accuracy of the WMMS model outputs, especially during summer months. Third, a procedure to include loss rates as an optimization constraint was devised. Including specific loss rates for a sub-watershed yielded poor results, so instead a constraint was devised to allow in-streamflows to deviate within a narrow range (.75 to 1.25) of the WMMS simulated flows calibrated to historic hydrology. This constraint represents evaporation and groundwater infiltration and is an important governing limitation for the analysis presented below.

2.5 Analysis Procedures

Modeling procedures included multiple runs for both the minimization and maximization formulations. For the maximization formulation to assess local water supply potential, model runs included ranges of water demands (60% to 100% of 2010 reported values) and imported water supplies (0 to 100% of historic import values), creating a matrix of outcomes. For the minimization scenario, model runs across a similar set of imported water inputs were performed, but reported results focused on a single scenario with imported water reductions of 50%. Water deliveries in the cost-minimizing formulation must meet a lower boundary for health and safety considerations, but otherwise are unspecified and subject to the low-cost seeking objective function.

Stormwater capture and use is optimized in both formulations. In the maximization formulation, it is designated as a local source and, as such, flows through all capture basins are maximized within constraints. In the minimization formulation, existing stormwater capture facilities are relatively cheap in comparison to other sources and are utilized as an important source of groundwater replenishment.

To assess the effects of stormwater capture and use in both formulations, several analyses were performed on the model outputs. First, the difference between optimized (*Artes*) and simulated (*WMMS*) streamflows were calculated for each modeled time step in each of the 47 watersheds in *Artes*. The differences were summed to annual values and averaged across a 15-year modeled period. Results were calculated in terms of both volumetric change and percent change. Second, differences in upstream and downstream flows were assessed. Third, median and average annual changes were compared to understand the extent to which a few extreme events skew the average results. Finally, summary results from the two formulations were examined to estimate the total overall effects that stormwater capture and use may have on urban streamflows.

3 Results

Results show that, without mitigating policies, emphasizing stormwater capture and use, either through policy mandates (maximizing flows) or economic incentives (minimizing costs) simulated through the alternative model formulations, could significantly reduce the volume of downstream flows. Several trends are evident. First, most watersheds, especially those below the stormwater capture basins primarily located in upper and middle watersheds, experience an average decrease in streamflow volumes. Calculating the median change (by volume) between simulated and optimized flows reveals significant decreases in streamflow volumes for both model formulations across most watersheds in LA County (Fig. 2a, b). For instance, watersheds in the downstream basins of the West Coast and Central Basins, along with the Lower Los Angeles River, all see annual volumetric decreases of more than 5000 acre-feet compared to the WMMS-based historic flows. Some watershed areas, however, are exceptions. In the flow maximization approach (Fig. 2a), upper watersheds (where much precipitation falls) experience higher flows as the optimization procedure prioritizes stormwater capture to fill upstream reservoirs in those areas. In the cost minimization approach (Fig. 2b), a few upstream basins experience increased flows, notably the watershed serving the Sepulveda Basin, which is modeled as having newly planned infrastructure to increase stormwater capture. In addition, several of the eastern watersheds along Coyote Creek, which eventually flow into the San Gabriel River, see higher volumetric flows, which likely correlates with several of the expanded flow capacities for alternative reuse and stormwater capture facilities based on documents.

Second, while volumetric decreases are similar between the modeling formulations, measuring change in terms of percent reveals differences between the modeling approaches (Fig. 2c, d). In the cost-minimizing approach (Fig. 2d), downstream watersheds still see significant differences, with the median value of change being 100% or more of historic values. Upper watersheds are more mixed, with several showing increases (by median) and others showing consistency. In the flow-maximizing approach, however (Fig. 2c), most watersheds see little or no decrease, and upper watersheds see significant increases. Thus, seeking low-cost options for stormwater capture and use may come at the expense of in-streamflows. Enacting policies to mitigate streamflow decreases, such as mandated in-stream flow requirements that ensure minimum flows based on empirical analysis, could potentially help in maintaining hydrologic patterns of recent decades.

Third, the difference in upstream and downstream watersheds is significant (Fig. 3). In both model formulations, upstream watersheds, especially in natural and sparsely populated areas in the mountains surrounding LA's cities, have similar or even more volumetric streamflow, driven by the optimization algorithm to route runoff into the network of upstream spreading grounds. Downstream basins, predictably, suffer more, with water being captured upstream depleting flows. Notably, in the simple model construct, there is no explicit link between

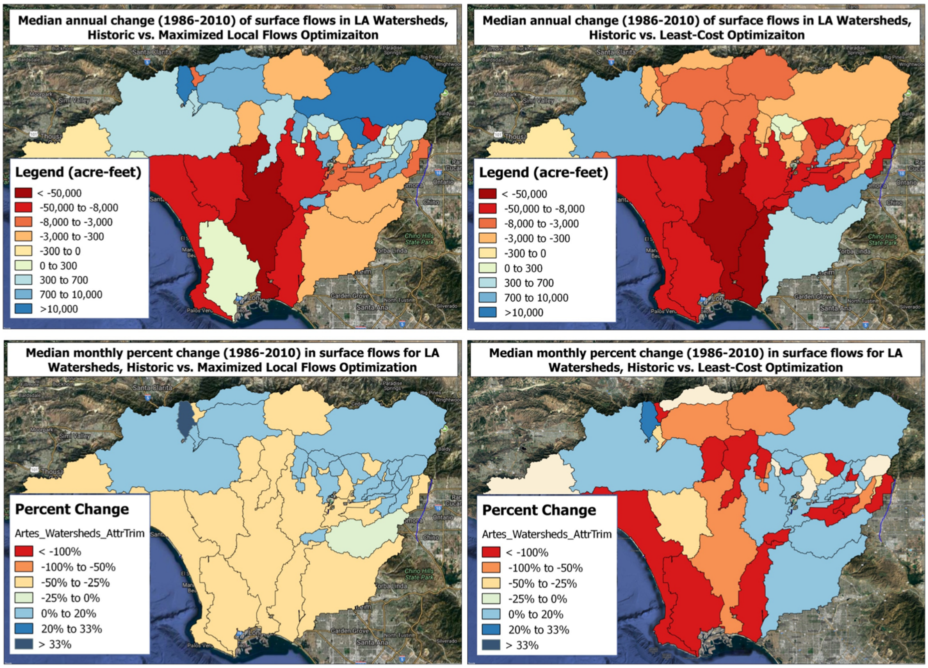

Fig. 2 Comparing annual (a,b) and monthly (c,d) differences in streamflow volume from optimization to either maximizing flows or minimizing costs

surface and groundwater flows. Capturing stormwater to recharge groundwater could help restore connectivity in the vadose zone in some areas and buffer streamflow losses. But, in model scenarios where the median percent change in monthly streamflow volumes is 100% or more, the augmentation of groundwater aquifers will likely not be sufficient to maintain current streamflows.

Fourth, seasonal variations are informative. Winter streamflows tend to be the same or decrease on average, while summer flows tend to increase. This may occur because during winter months with precipitation, stormwater is being captured and infiltrated, while during summer months, any in-stream flows are allowed to remain in streams and channels to reach important end-uses, such as water reuse plants or a few downstream spreading grounds (Fig. 4).

4 Discussion

Urban streams have many beneficial uses, including aquatic habitat, recreation, water supply, and groundwater recharge. They can also be a direct, lifeline source of water for some disadvantaged and homeless populations, an old fact of life that is still highly relevant in contemporary cities (Engels 1887). As such, the study intended to demonstrate how emphasizing management goals of capturing more volumes of stormwater, an engineering solution,

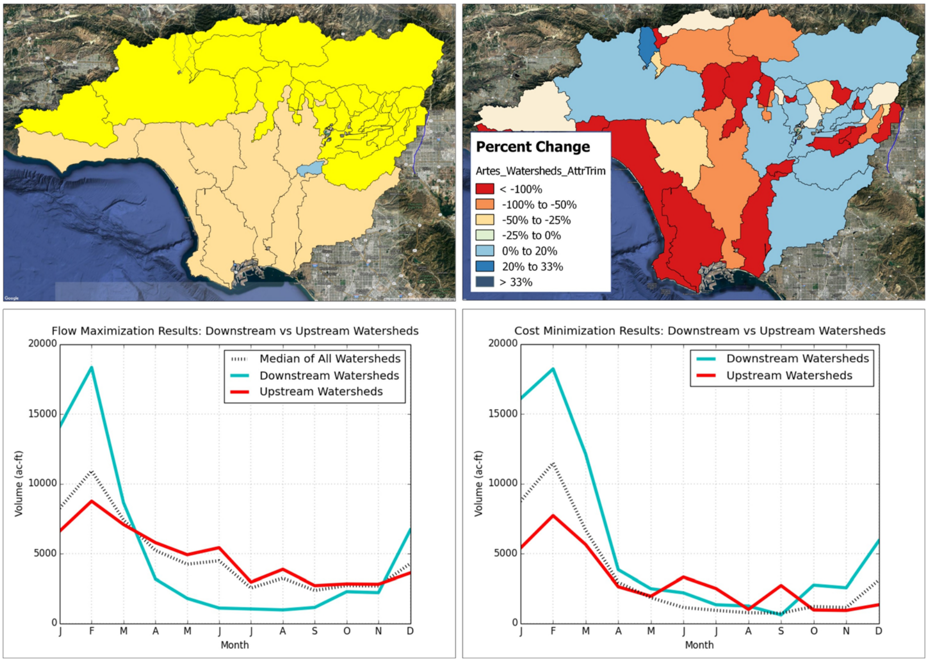

Fig. 3 Comparing streamflow volume in upstream and downstream watersheds for optimized scenarios: a) map showing upstream and downstream watersheds, b) median annual change in the cost minimization model run, showing differences in upstream and downstream basins, c) average monthly volume in downstream vs upstream watersheds for flow maximization formulation, compared to median of all watersheds, d) average monthly volume in downstream vs upstream watersheds for cost minimization formulation, compared to median of all watersheds

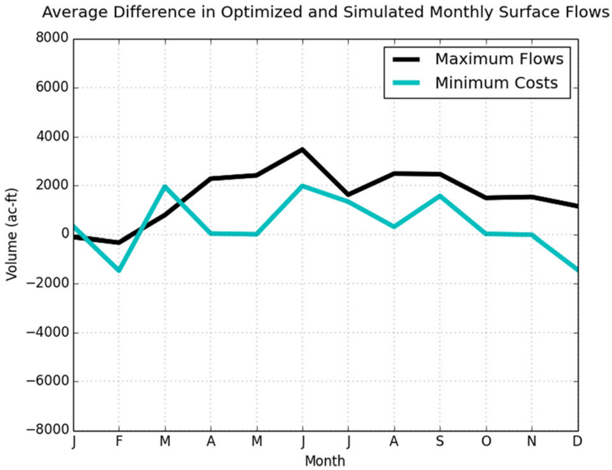

Fig. 4 Average difference in monthly streamflow volume between simulated and optimized model results for each model formulation

could have unforeseen downstream consequences for both habitat and people in years of moderate and low precipitation. If water agencies pursue more stormwater capture en route to greater local water supply reliance, carefully including environmental scientists and environmental advocacy groups is important to ensure that water supply strategies do not dominate other beneficial uses, as is often the case in arid areas (Hundley 2001).

California offers a useful case study to understand tradeoffs in urban development and environmental management. Across much of California, current policy processes are identifying requirements for in-stream flows that would support productive aquatic habitat. In coastal Southern California, streamflows that run from the mountains to the ocean are important sources of freshwater for aquatic habitat and estuaries, though few productive estuaries remain and even these will be further stressed by climate change (Rogowski et al. 2015; Thorne et al. 2016). Maintaining streamflows of reasonable quantity and quality in the highly urbanized basins is a task requiring active watershed management. The outcomes are not clear. For instance, capturing and infiltrating more stormwater could boost groundwater basin levels that, in turn, increase in-stream flows through surface and groundwater connectivity. But, parallel regional goals for water conservation would decrease in-stream flows, as less water would be discharged to streams (Manago and Hogue 2017). The exact balance of these contributing factors is uncertain, but this modeling provides empirical evidence of the potential for significantly reduced seasonal streamflows in important urban rivers and streams.

5 Conclusions

The analysis presents a methodology for analyzing the effects of a set of policies that are generally viewed as more “sustainable” (reduced imported water inflows and increased reliance on local supply sources) but, as with all management decisions, incur tradeoffs. In this case, increasing stormwater capture for local water supply enhancement could result in significantly reduced streamflow volumes. More stringent engineered infrastructure and operational policies to capture runoff, simulated in this analysis through a model with optimization, yields noticeable reductions in streamflows across the study region. While some results from optimization likely overestimate the volume of water that could be captured, the potential for unforeseen consequences from management goals and engineering solutions is significant (Tarr et al. 1984). Establishing environmental flow requirements that correspond with aquatic habitat and recreational uses can help promote multi-benefit use of urban rivers. While many political, economic, and hydrologic factors will likely drive agencies in drier climates such as Los Angeles to better utilize local sources, without considering environmental and social objectives in planning, outcomes of environmental degradation and social inequity are, at least, possible.

Compliance with Ethical Standards

Conflict of Interest Statement The authors certify that they have no conflicts of interest.

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