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Research papers

# Balancing water reuse and ecological support goals in an effluent dominated river

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A B S T R A C T

Flows in urban rivers are increasingly managed to support water supply needs while also protecting and/or restoring instream ecological functions, goals that are often in opposition to each other. Effluent-dominated rivers (i.e., rivers that consist primarily of discharged treated wastewater) pose a particular challenge because changes in effluent discharge may impact river ecology. A functional flows approach, in which metrics from the annual hydrograph correspond to ecological processes, was applied to understand the hydro-ecological implications of wastewater reuse in the Los Angeles River watershed (Los Angeles County, California, USA). The Los Angeles River, like many urban rivers, is dominated by effluent, particularly during dry weather. An hourly hydrologic model was created, calibrated, and validated in EPA SWMM for the Los Angeles River watershed to investigate how increases in wastewater reuse (i.e., decreases in discharge to the river) may impact river flows and subsequently ecology and recreation in the river. Current flows are shown to support freshwater marsh, riparian habitat, fish migration, and wading shorebird habitat, in addition to recreational kayaking. Functional flow metrics were assessed under future management scenarios including reducing discharge to increase recycling at three wastewater treatment plants within the watershed. Both wet-season and dry-season baseflows were most sensitive to increasing wastewater reuse, with an average decrease of 51–56% (0.93 cms) from current baseflows. Sensitivity curves that relate potential changes in wastewater discharge to changes in functional flows show that a 4% decrease in current wastewater discharge may negatively impact habitat for indicator species during the dry season. More opportunity exists for wastewater reuse during the wet season, when current wastewater discharge may be reduced by 24% with minimal impacts to ecology and recreation. The developed approach has the potential to inform similar tradeoff decisions in other urban rivers where flows are dominated by wastewater or stormdrain discharge.

## 1. Introduction

Management of urban water infrastructure is increasingly complicated as cities plan for drought, climate change resiliency, and population growth. Urban water management has historically relied on siloed government entities, each responsible for a different component of the urban water cycle (e.g., stormwater, wastewater, drinking water). This traditional approach has been found to be ineffective in managing the complexity of urban water flows (Escriva-Bou et al., 2016). Moreover, importing large volumes of water from distant locations is becoming more costly and politically contentious as potentially competing demands increase. A "One Water" approach has been proposed for cities to sustainably manage their limited and valuable water supplies (Mukheibir et al., 2014). The "One Water" approach builds on the concept of integrated water resources management (IWRM) and emphasizes collaboration and coordination amongst water stakeholders and decision-makers (Daigger et al., 2019; Luthy et al., 2019). Communities committed to this approach include many in Australia, hit hard by the Millennium Drought, Israel, Los Angeles, California, and other arid cities in the western United States.

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Effluent-dominated rivers, which are common in arid urban areas, are particularly challenging to manage without a holistic approach because wastewater discharge is directly connected to surface waters. In these systems, wastewater was historically considered a waste stream but is now viewed as a resource for water, energy, and material (i.e., fertilizer) recovery (Guest et al., 2009; United States Environmental Protection Agency, 2019). For example, wastewater reuse is now a key component of California's water supply, with over 9% of the state's urban water demands met by treated wastewater augmenting reservoir, groundwater, and raw water supplies (WateReuse California, 2019). Alternatively, managed wastewater discharge can provide an opportunity to support environmental flows, or flows required to sustain river ecosystems (Lawrence et al., 2014). Wastewater effluent can be used to align flows more closely to the natural flow regime (Eppehimer et al., 2020) or to create and maintain novel ecosystems that would likely not exist under natural conditions (Luthy et al., 2015; White and Greer, 2006). For example, in Calera Creek in Pacifica, California, flow augmentation from treated wastewater effluent converted a naturally intermittent stream into a perennial one, which allowed for the creation of lost habitat for rare and endangered species and support of recreational opportunities (Halaburka et al., 2013). While there are numerous success stories of wastewater recovery and reuse, management decisions for water supply and environmental flows are often made independently of one another, and there is a critical need for tools and approaches to balance potentially competing goals of reuse and supporting ecological communities. The majority of studies on effluent-dominated streams focus on water quality and stream temperature issues, and very few studies are focused on flow management applications (Hamdhani et al. 2020).

Existing approaches for managing environmental flows in effluent-dominated rivers typically consist of limiting withdrawals to a fixed proportion of the natural flow regime. This approach may maximize water for reuse but may not guarantee that ecological objectives can be achieved (Richter et al., 2012). A *functional flows* approach offers a more holistic method that accounts for the complexity and variability of flow over space and time and aims to protect the ecological integrity of the river but allow for flexibility for water reuse during ideal times. In a functional flows approach, the annual hydrograph is segmented into discrete components that have ecological significance in a river system (Yarnell et al., 2015). The components are described by flow characteristics that include frequency, timing, magnitude, duration, or rate of change (Poff et al., 1997), and support biophysical processes, which subsequently provide functions for native biological communities. For example, dry-season baseflow can maintain critical habitat for native aquatic species (Kupferberg et al., 2012; Postel and Richter, 2003; Yarnell et al., 2016), and peak flows can support fish rearing and spawning in the floodplain (Jeffres et al., 2008; Opperman et al., 2017). Together, functional flow metrics provide a quantitative framework for managing environmental flows to support critical ecosystem functions (Yarnell et al., 2020).

Using the Los Angeles (LA) River watershed as a case study, we assess the relationship between wastewater discharge and functional flow metrics and evaluate the impact of reduced wastewater discharge on aquatic life and recreational uses. The main research questions addressed in this study are:

1. How sensitive are functional flows in the LA River to changes in wastewater discharge?
2. What is the impact of wastewater reuse on recreational uses and ecology in the LA River?
3. How can tradeoffs in environmental flows and wastewater reuse be evaluated to better inform management decisions?

Our developed approach provides a framework for integrated water resources management and can be applied to other urban watersheds that have challenges balancing water supply with environmental flows.

## 2. Methods

### 2.1. Study area

#### 2.1.1. Site Description

The LA River watershed is in Los Angeles County, CA, USA and is 2,160 km$^2$. Approximately 32% of the watershed is impervious and dominant land uses include residential, open space, and commercial. The upper tributaries of the watershed are in steeply sloped mountains where much of the landscape is forested and unaltered. The lower portions of the watershed, which drain to the mainstem and other tributaries, are highly urbanized. Slopes within the watershed vary from 20% in the northern national forest to 0.2% in the densely urbanized lower watershed (average = 8%). The regional climate is Mediterranean with wet winters and dry summers. The average annual precipitation varies spatially in the catchment, from about 200 to 460 mm (8 to 18 in.). The lower portion of the watershed is highly altered for water supply and flood control; most of the mainstem of the river is channelized except for two key soft-bottom reaches, Glendale Narrows and Sepulveda Basin. There are eight major dams located within the watershed. Many of the channelized reaches have low flow "notches" concentrating flows during the dry season. Several spreading grounds are also operated within the watershed and are designed to capture stormwater, treated wastewater, or imported water to recharge aquifers.

Three water reclamation plants (WRPs) are located within the watershed: Glendale, Burbank, and Donald C. Tillman (Tillman), which discharge a combined average of about 2 m$^3$/s (71 cfs, 45.9 MGD) to the river annually. The cities of Burbank, Glendale, and Los Angeles have decreased or plan to gradually decrease discharges of treated wastewater to the river. Both Burbank and Glendale have filed water right change petitions, under CA Water Code Section 1211, with the State Water Resources Control Board to decrease their annual discharge by 30% and 33%, respectively (California State Water Resources Control Board, 2017a, 2017b). Tools developed in this study will inform decisions regarding the 1211 change petitions.

The LA River watershed presents a unique opportunity to evaluate the impacts of wastewater reuse on environmental flows given: (1) the County of Los Angeles is water-stressed, with 57% of municipal water imported from outside of the region (Los Angeles Department of Water & Power 2016); (2) the City of Los Angeles has adopted a "One Water" approach to manage water holistically (City of Los Angeles 2018); (3) the LA River is altered for flood prevention (nearly entirely channelized) and wastewater makes up the majority of flow during the dry season; and (4) several municipalities within the watershed have started or plan to reuse more wastewater to supplement drinking water (California State Water Resources Control Board, 2017b, 2017a). Water management, hydrology, and water quality in the LA River watershed have been studied extensively (Abdi et al., 2021, 2020; Gallo et al., 2020; Pincetl et al., 2019, 2016; Porse et al., 2017; Read et al., 2019; Wolfand et al., 2018).

#### 2.1.2. Focal reaches

Twelve locations (herein referred to as reporting nodes) were selected within the mainstem to represent specific reaches of the river (Fig. 1). Detailed results from two of these nodes are reported in this study as they serve as illustrative examples for the river: (1) the Glendale Narrows (abbreviated GLEN) and (2) the lower reach of the LA River mainstem (abbreviated LA3). These two locations were chosen because GLEN is located downstream of all wastewater inputs to the river but upstream of several major tributaries, while LA3 is located near the outlet, close to where the river becomes brackish (Fig. 1).

The Glendale Narrows is one of the last remaining soft-bottom portions of the river downstream of the wastewater treatment plants (Fig. 1). Historically, this 13-km reach was not fully channelized because of groundwater upwelling within the reach (Fig. 1) (Upper LA River Area Watermaster 2018). Because of this, the Glendale Narrows is a

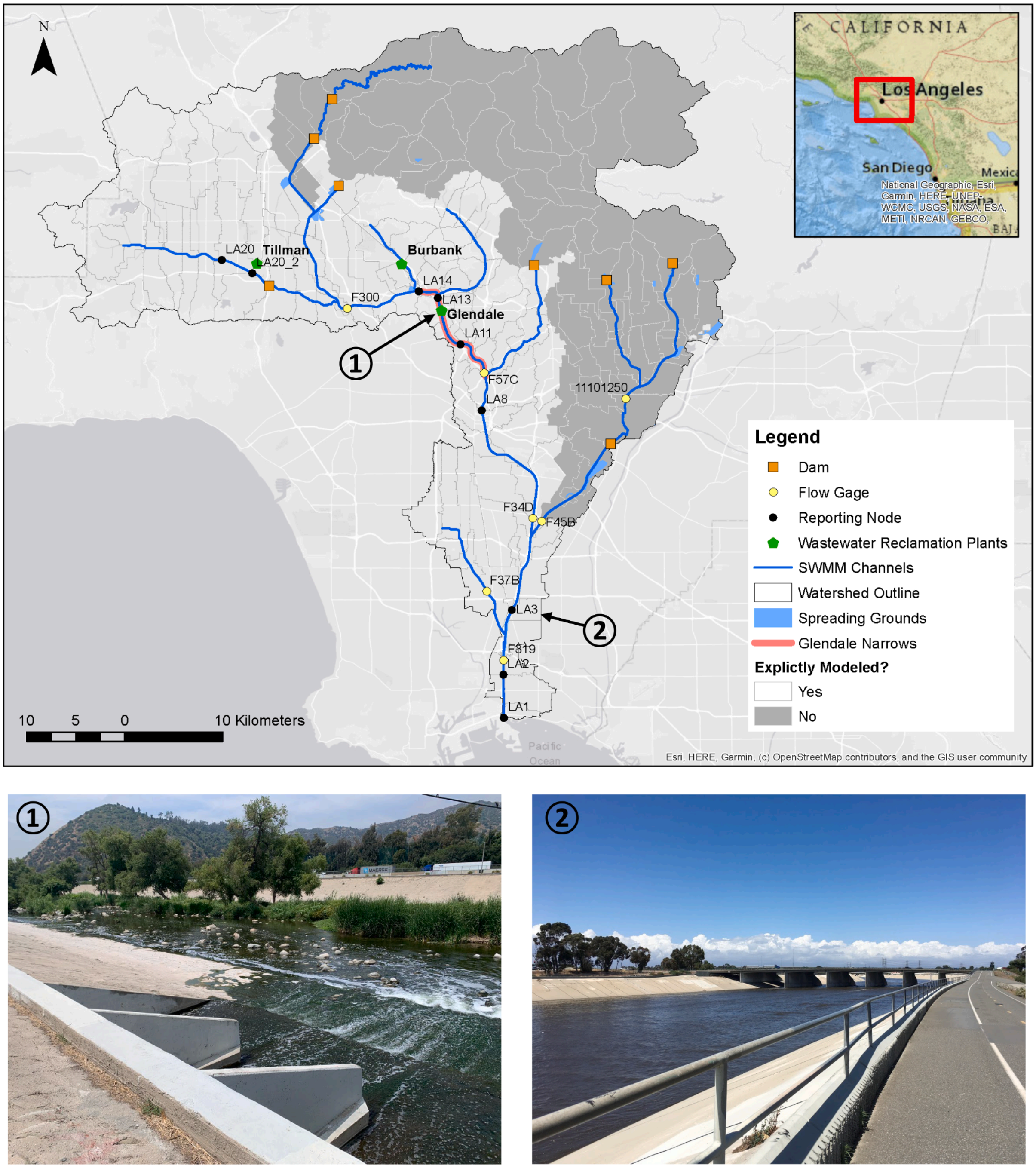


**Fig. 1.** Map of the LA River watershed, Los Angeles County, CA, and photos of the locations used as illustrative examples in this study: (1) the Glendale Narrows (GLEN) soft-bottom reach (note the vegetation growing in the channel), and (2) the lower LA River mainstem (LA3), which is constructed of concrete.

unique location within the mainstem of the river that supports both recreational uses and habitat for a variety of riparian-dependent and aquatic species. Beneficial uses within the Glendale Narrows include warm freshwater habitat and wildlife habitat. Existing species of concern that are riparian-dependent and may be impacted by flow reductions include, but are not limited to, the yellow warbler, least Bell's vireo (endangered), and the willow flycatcher (endangered) (Stein et al., 2021). Opportunities exist to improve habitat for existing species and species that could be reintroduced, such as the cold-water Santa Ana sucker (Abdi et al., 2021; Stein et al., 2021).

The lower reach of the LA River mainstem (LA3) is just upstream of the estuary and receives flow from the entire watershed. This reach contrasts to the Glendale Narrows because it is completely channelized with concrete (Fig. 1). The LA3 reach supports fish migration, warm water fish, and wading shorebirds.

Both Glendale Narrows and the lower LA River support a variety of recreational uses such as wading, kayaking, horseback riding, and fishing within the channel as well as activities such as biking, bird-watching/wildlife viewing, walking/jogging, and community and educational events adjacent to the channel. In 2019 the Council for Watershed Health completed a study of the LA River quantifying the flows required to maintain the recreational uses within each reach of the river. Through a series of interviews and analysis of social media, they determined that activities that occur within the river channel, along with birdwatching/wildlife viewing and aesthetic enjoyment, are dependent on flows in the river. For most activities, it was difficult for experts to name precise flow requirements, but a depth of 15 to 91 cm (6–36 in.) in the Glendale Narrows was estimated for supporting wading, boating, and fishing activities. Recreational experts also noted that water depth was important for sustaining aesthetic uses of the river such as painting, photography, or general scenic enjoyment. Wildlife viewing is also affected by flows as different species require different habitat conditions (Stein and Sanchez, 2019).

### 2.2. Overall approach

A hydrologic model was created in EPA SWMM for the LA River watershed, which includes the mainstem of the LA River and two major tributaries, Compton Creek, and Rio Hondo. EPA SWMM is a hydrologic model commonly used to simulate stormwater runoff in urban catchments (U.S. Environmental Protection Agency, 2017). Model inputs include precipitation, evapotranspiration, impervious cover, slope, and infiltration parameters (described in more detail in Section 2.3). The model was created with an hourly time step from the water year 2011 to 2017. This period was chosen because (1) high-resolution (hourly) data was available for wastewater discharge, in-stream flows, dam operations, and spreading grounds, and (2) wastewater discharge during this period remained relatively constant, so the period is representative of baseline conditions without substantial wastewater reuse. The model was calibrated from the water year 2011 to 2013 and validated from the water year 2014 to 2017 at 7 gaged locations throughout the watershed (4 on the mainstem, 3 on tributaries).

Potential wastewater discharge scenarios were generated using a Monte Carlo approach in which historic wastewater discharge time series from the water year 2011 to 2017 were randomly scaled by 0 to 100% for 500 simulations (Section 2.4). In addition, 100% and 50% reduction of dry-weather stormdrain discharge scenarios were simulated (Section 2.5). Discharge was evaluated at 12 reporting nodes along the mainstem (Section 2.1) to evaluate the impact of reduced wastewater discharge on recreation and aquatic life. Functional flow metrics (Table 3), such as dry-season baseflow magnitude and wet-season timing, were quantified using the Functional Flows Calculator API client package in R (version 0.9.7.2, https://github.com/ceff-tech/ffc_api_client), which uses hydrologic feature detection algorithms developed by Patterson et al. (2020) and the Python functional flows calculator (https://github.com/NoellePatterson/ffc-readme).

### 2.3. Hydrologic model setup

#### 2.3.1. Spatial data

Sewersheds were downloaded from the LA County Watershed Management and Modeling System (Tetra Tech, 2020). These sewersheds were merged into 77 catchments with an average size of 15.8 $km^2$ (3900 ac). The storm sewer network, retrieved from the LA County GIS data portal (County of Los Angeles, 2020), as well as the National Hydrography Dataset (U.S. Geological Survey, 2019) flowlines, were used to confirm the drainage network. A Digital Elevation Model (DEM) was retrieved from the United States Geological Survey (USGS) 3D Elevation Program at 1/3 arcsecond resolution and processed to find the average slope for each subcatchment (U.S. Geological Survey, 2016a). Total imperviousness for each catchment was estimated from the National Land Cover Database (U.S. Geological Survey, 2016b). Soils data was downloaded from the Natural Resources Conservation Service, United States Department of Agriculture Soil Survey Geographic Database (Natural Resources Conservation Service, 2019). Green-Ampt infiltration parameters (hydraulic conductivity, suction head, moisture deficit) were initially estimated by matching Natural Resources Conservation Service hydrologic soil groups to typical values and spatially averaging. Areas with no hydrologic soil information were assumed to be Group D, which is characteristic of soils in urban areas with low infiltration capacity (National Resources Conservation Service, 2007). Channel geometry was not included in the hydrologic model. A separate hydraulic model was created with the Hydrologic Engineering Center's River Analysis System (HEC-RAS) and detailed in a separate study (Stein et al., 2021).

#### 2.3.2. Time series data

Potential evapotranspiration (PET) data was downloaded from the California Irrigation Management Information System (CIMIS), which is a collection of autonomous weather stations that make real-time observations (California Department of Water Resources, 2019). The inverse-distance square weighing method (Longley et al., 2015) was used to combine the reference PET time series from the nine closest CIMIS stations into one for the centroid of the LA River watershed (Table S1), and applied to subcatchments throughout the watershed.

Precipitation data was retrieved for 72 of the Los Angeles County Automatic Local Evaluation in Real Time (ALERT) rain gages. Precipitation was spatially interpolated for each catchment by kriging using the krige function from the R package gstat, with a variogram generated through the function 'fit.variogram' from the same package, using a spherical variogram for the best fit (R Core Team, 2020).

Flow data at 29 gaging stations was retrieved from the Los Angeles County Department of Public Works and at 6 gaging stations from the USGS. Spreading basin data was retrieved from the Los Angeles County Department of Public Works for 15 facilities. These facilities recharge a mix of imported, recycled, and stormwater. Because the distribution of these water sources changes annually, current conditions at spreading basins were not modeled explicitly; effects from spreading basins were captured by adjusting calibration parameters.

Data was retrieved from the City of Los Angeles for discharges from the Tillman and the Glendale WRPs. Timeseries discharge for Burbank WRP to the LA River was retrieved from the State Water Resources Control Board. Inflow and outflow data for five dams within the watershed were retrieved from the Los Angeles County Department of Public Works: Eaton Wash, Devil's Gate, Big Tujunga, Pacoima, Santa Anita. Whittier Narrows Dam and Sepulveda Dam data were downloaded from the USGS website.

Most of the dams are in the upper reaches of the LAR watershed and capture runoff from primarily open space or undeveloped land. Because we were interested in the impact of wastewater discharge scenarios that affect flow in the urban parts of the watershed, the dams were not explicitly modeled (Fig. 1). Rather, we represented the dams as model nodes with inflow time series.

Baseflow was separated from event flow using the USGS hydrograph separation program (HYSEP) and distributed across each reach based on contributing catchment area (Sloto and Crouse 1996). The exception for this was in the Glendale Narrows area where baseflow was disaggregated to include groundwater upwelling, WRP discharge, and channel evaporation. Groundwater upwelling in the Glendale Narrows was assumed to be a constant discharge over the year at around 3,000 acre-ft/yr (0.12 cms) (Upper Los Angeles River Area Watermaster, 2018). Evaporation within the channel was estimated by multiplying monthly pan evaporation data collected at Long Beach, CA by a coefficient of 0.75.

#### 2.3.3. Calibration and validation

The hydrology model was calibrated at 7 gage stations from upstream to downstream using an automated calibration tool to optimize the calibration parameter set from 500 to 1000 trials (Alamdari, 2016). Nash Sutcliffe Efficiency (NSE) was maximized, and percent bias was minimized (equally weighted) to select the best calibration parameter set. Calibration parameters included subcatchment width, hydraulic conductivity, depression storage, Manning's roughness coefficients, and percent directly connected impervious area. Calibration was considered "good" to "very good" (Moriasi et al. 2007) with NSE between 0.67 and 0.94 and percent bias between −20% and 17.3% (Table 1). Validation was satisfactory to very good (D. N. Moriasi et al., 2007) with NSE between 0.66 and 0.92 and percent bias between −19.9% and 17.3%

**Table 1**
Calibration and validation statistics for the hydrologic model of the LA River watershed. WY = water year.

| Gage ID | Gage Description | Drainage Area ($km^2$) | Calibration (WY 2014–2017) | | | Validation (WY 2011–2013) | | |
|---|---|---|---|---|---|---|---|---|
| | | | NSE | % Bias | $R^2$ | NSE | % Bias | $R^2$ |
| F37B | Compton Creek | 60 | 0.70 | −14.9 | 0.72 | 0.66 | 17.3 | 0.81 |
| E285 | Burbank Western Channel | 65 | 0.72 | 3.3 | 0.75 | 0.73 | −9.1 | 0.85 |
| F252 | Verdugo Wash | 70 | 0.67 | 2.6 | 0.69 | 0.75 | −19.9 | 0.75 |
| 11092450 | LAR above Sepulveda | 409 | 0.92 | −2.9 | 0.92 | 0.86 | −3.5 | 0.88 |
| F300 | LAR below Tujunga Wash | 1039 | 0.94 | 0.9 | 0.94 | 0.90 | −14.4 | 0.91 |
| F57C | LAR above Arroyo Seco | 1323 | 0.76 | −9.7 | 0.76 | 0.92 | 13.8 | 0.94 |
| F319 | LAR below Wardlow Rd. | 2111 | 0.80 | −11.9 | 0.81 | 0.90 | −5.4 | 0.91 |

(Table 1). Example calibration and validation plots are shown in Fig. 2, and an example comparison of observed and simulated time series data is provided in Figure S1.

### 2.4. Wastewater reuse scenarios

A Monte-Carlo approach was used to simulate a wide range of potential WRP reuse scenarios in the watershed including multiple combinations of reuse from each WRP, as opposed to a discrete set of reuse scenarios (i.e., all treatment plants reuse 0%, 25%, 50%, 75%, or 100%). This approach allows for flexibility of potential future management options that can be implemented to achieve objectives. Historic time series of WRP discharge from the water year 2011 to 2017 were scaled by 0 to 100% for 500 random simulations. Scenarios were summarized by the average annual seasonal (i.e., wet or dry season) WRP discharge over the simulation period (Equation (1)). For example, for a scenario with a scaling of 25% discharge, 50% discharge, and 75% discharge for Tillman, Burbank, and Glendale, respectively, the average WRP discharge for the dry season would be 0.74 $m^3/s$ (26.0 cfs; 16.8 MGD) and 0.89 $m^3/s$ (31.4 cfs; 20.3 MGD) for the wet season.

$$Q_{WRP} = S_{Tillman}{}^{*}\overline{Q}_{Tillman} + S_{Burbank}{}^{*}\overline{Q}_{Burbank} + S_{Glendale}{}^{*}\overline{Q}_{Glendale} \tag{1}$$

*Where:* $Q_{WRP}$ = Average seasonal wastewater discharge to the LA River.

$S$ = Scaling factor for each WRP.

$\overline{Q}$ = Average seasonal discharge from each WRP.

### 2.5. Stormdrain discharge scenarios

Dry-weather stormdrain discharge, defined as industrial discharges and as any flows running off the land surface and into the LA River that are not a result of a precipitation event (i.e., irrigation, car wash return-flows, or shallow groundwater dewatering operations), was simulated using a water budget approach (Eq. (2)–(4)). Dry-weather stormdrain discharge is likely to decrease substantially over the next several years as the City of Los Angeles plans to install dry weather low flow diversion systems to improve water quality and comply with total maximum daily load requirements (TMDLs) (City of Los Angeles et al., 2020). Two additional scenarios were therefore included in the simulation: 50% and 100% reduction in dry-weather stormdrain discharge.

$$Q_{tot\_sim} = Q_{storm\_runoff} + Q_{baseflow} - Q_{dam} \tag{2}$$

$$Q_{baseflow} = Q_{WRP} + Q_{upwelling} + Q_{industrial} + Q_{non-stormrunoff} \tag{3}$$

$$Q_{dry\_weather\_stormdrain\_discharge} = Q_{industrial} + Q_{non-stormrunoff} \tag{4}$$

Where:

$Q_{tot\_sim}$ = total simulated discharge.

$Q_{storm\_runoff}$ = storm runoff, simulated in EPA SWMM.

$Q_{baseflow}$ = baseflow.

$Q_{dam}$ = discharge impacts from dams, can be either positive or negative, based on historic data.

$Q_{WRP}$ = WRP discharge, based on historic data.

$Q_{industrial}$ = industrial discharges.

$Q_{non\text{-}storm\ runoff}$ = discharge due to land surface runoff not due to storm events, such as irrigation return flows and car-washing.

### 2.6. Functional flow metrics

Flow was summarized using a suite of 24 functional flow metrics that quantify characteristics of the annual hydrograph that support a broad suite of ecological functions (Yarnell et al., 2020). These metrics

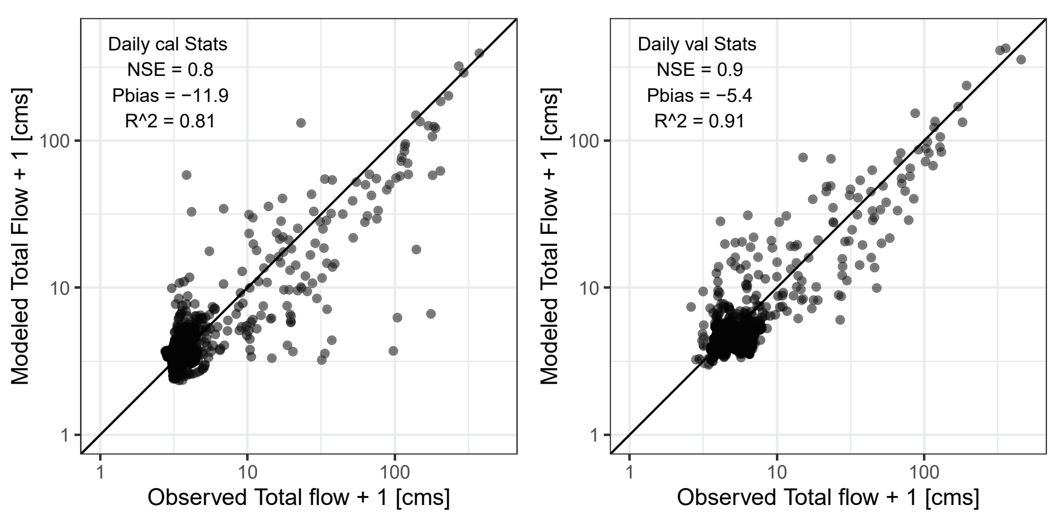


**Fig. 2.** Calibration (left) and validation (right) performance of the SWMM hydrologic model at the LA County flow gage F319 (LA River below Wardlow Rd.). Note the log–log scale.

aggregate flow data into five flow components: fall pulse flow, wet-season baseflows, peak flows, spring recession flows, and dry-season baseflows, which represent different features of the annual hydrograph that are specific to California streams. Ranges of values for the 24 functional flow metrics were used to determine the degree to which each flow component can support characteristic biological communities, and to assess the degree of hydrologic alteration in comparison to baseline conditions. See Supplementary Material for additional background on functional flows.

Functional flow metrics were compared longitudinally from upstream to downstream under baseline conditions to evaluate the relative contribution of WRP discharge on functional flows. For the 500 reuse scenarios, functional flow metrics were calculated at Glendale Narrows (GLEN) and in the lower reach of the mainstem (LA3) to determine which flow metrics are most sensitive to changes in wastewater discharge.

### 2.7. Flow targets for beneficial uses

Recommended flow ranges for ecological and recreational uses in the LA River used in this study were compiled from previous work (Table 2) (Stein and Sanchez, 2019; Stein et al., 2021). Briefly, flow conditions necessary to support the life-history needs of several "focal" species were determined and used to create "flow-ecology" curves or models relating key hydrologic and hydraulic variables to the probability of occurrence for each focal species, or the probability of being able to complete specific life-history requirements. Focal species for the Glendale Narrows (GLEN) include cattails (*Typha* spp.), indicative of freshwater marsh habitat, and black willow (*Salix gooddingii*), indicative of riparian habitat. The Glendale Narrows also supports recreational kayaking. Focal species in the lower mainstem of the LA River (LA3) are steelhead trout (*Oncorhynchus mykiss*) and green algae (*Cladophora* spp.). Large populations of wading shorebirds use the lower mainstem of the LA River and eat the green algae. Steelhead trout have historically used the mainstem of the LA River as a migratory passage to spawning grounds in the upper tributaries, but they are not currently observed in the river. The percentage of simulation years that had dry-season and wet-season baseflows within the recommended flow ranges for each focal species was calculated for GLEN and LA3 over the 500 wastewater reuse scenarios.

### 2.8. Sensitivity curves

Flow-based sensitivity curves were developed that relate changes in WRP discharge to functional flow metrics. For each scenario, the range of flow metric values from the 10th, 50th, and 90th percentiles were plotted against the average seasonal WRP discharge to account for the variability in flow metric values from each scenario across the period of record. Curves were developed for the dry-season baseflow (50th percentile of mean daily flow during the dry season) and wet-season baseflow (10th percentile of mean daily flow during the wet season) magnitude metrics. The wet-season metrics, baseflows from the start of the storm season to the start of the dry season, and dry-season metrics, baseflows from the start of the dry season to the start of the following wet season, were calculated on an annual basis. Typically, the start of the wet season is between November to January and the start of the dry season is between May to July depending on the climatic conditions for a given water year.

Sensitivity curves were used in combination with recommended flow ranges (Table 2) to determine wastewater discharge needed to support aquatic life and recreational uses.

**Table 2**
Baseflow targets for beneficial uses at the Glendale Narrows (GLEN) and lower LA River (LA3). The flow limits provided are for the baseflow magnitude functional flow metric. Flow targets use in this study correspond to "medium" probability of occurrence as reported in Stein et al. 2021; Stein and Sanchez 2019.

| Location | Habitat | Focal Species | Season | Flow Limit (cms) | |
|---|---|---|---|---|---|
| | | | | Lower | Upper |
| Glendale Narrows (GLEN) | Freshwater marsh | Cattail | Dry | 2.18 | 4.7 |
| | | | Wet | 2.18 | 16.1 |
| | Riparian | Willow | Dry | 0.65 | 10.1 |
| | | | Wet | 0.65 | 10.1 |
| | Recreational Use | Kayaking | Dry | 1.84 | 7.16 |
| | | | Wet | NA | NA |
| Lower LA River (LA3) | Migration | Steelhead | Dry | 1.76 | 76.4 |
| | | | Wet | 1.76 | 76.4 |
| | Wading Shorebird | Green Algae | Dry | 1.75 | NA |
| | | | Wet | 1.75 | NA |

**Table 3**
Functional flow median metric values for baseline conditions in the Glendale Narrows (GLEN) with 10th to 90th percentile ranges in parentheses. Duration metrics are expressed as the number of days, from start to end. Timing metrics are days of the water year, where October 1 is numbered 1. Flood frequencies are the number of times in which a given peak flow recurrence interval is exceeded in a year. The spring rate of change is the spring flow recession rate (percent decrease per day over the spring recession period).

| Flow Metric | Values | Units |
|---|---|---|
| Fall pulse duration | 2 (1–4) | days |
| Fall pulse start timing | Oct 8 (Oct 4-Oct 22) | |
| Fall pulse magnitude | 8 (7–33) | cms |
| Wet-season baseflow duration | 129 (48–184) | days |
| Wet-season baseflow start timing | Nov 26 (Nov 10-Jan 9) | water year day |
| Wet-season 10th percentile baseflow | 2.6 (2.1–3) | cms |
| Wet-season median flow | 3.1 (2.4–3.7) | cms |
| 10-year peak flow duration | 1 | days/year when present |
| 5-year peak flow duration | 1 | days/year when present |
| 2-year peak flow duration | 1.5 (1–2.7) | days/year when present |
| 10-year peak flow magnitude | 262 | cms |
| 5-year peak flow magnitude | 216 | cms |
| 2-year peak flow magnitude | 104 | cms |
| 10-year peak flow frequency | 1 | events/year when present |
| 5-year peak flow frequency | 1 | events/year when present |
| 2-year peak flow frequency | 1.5 (1–2.7) | events/year when present |
| Spring duration | 34 (14–139) | days |
| Spring start timing | Apr 13 (Feb 27-May 12) | water year day |
| Spring start magnitude | 82 (15–262) | cms |
| Spring rate of change | 0.03 (0.01–0.05) | % |
| Dry-season duration | 198 (121–237) | days |
| Dry-season start timing | May 25 (Apr 16-Aug 16) | water year day |
| Dry-season median baseflow | 2.25 (2–2.5) | cms |
| Dry-season 90th percentile baseflow | 2.47 (2.3–2.7) | cms |

## 3. Results & discussion

### 3.1. Current conditions

#### 3.1.1. Functional flow metrics

The LA River generally experiences a long dry season from mid-May to mid-November and a wet season from approximately mid-November to mid-March (Fig. 3). Dry-season baseflow magnitude ranged from 2 to 2.7 cms with a duration of 121 to 237 days. Wet-season baseflows ranged from 2.1 to 3.7 cms with a median duration of 129 days. The

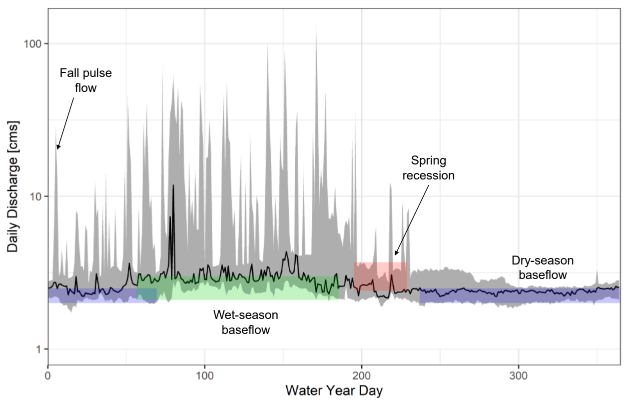


**Fig. 3.** Functional flow components for the Glendale Narrows are depicted on a representative hydrograph. The grey band represents the 90th to 10th percentile of daily discharge values and the black line represents median daily discharge from model outputs (water year 2011 to 2017). The green band shows the wet-season baseflow period, the red box shows spring recession, and the blue band shows dry-season baseflow. The width of the bands corresponds to the 10th and 90th percentile of flow metric magnitude values.

median flow metric values for GLEN are shown in Table 3 along with the range in values from the 10th to 90th percentiles.

Certain flow components are not well represented in the LA River, which we expect is similar to other flashy systems in semi-arid regions. For example, the fall pulse flows can be important for the initial flushing of fine sediments and "priming" of the system for subsequent winter storms. However, in the LA River, such pulse flows seldom support these functions because of the lack of natural substrate, stochastic nature of early season storms, and the fact that the first storms of the season are often captured through stormwater infrastructure for water quality purposes. In the LA River, fall pulse flows rarely occurred, but when they did, they occurred in October with a magnitude ranging from 7 to 33 cms. Similarly, pronounced spring recession flows are often absent in the LA River due to the lack of snowmelt runoff, lack of strong groundwater influence, and channelized nature of the river which hastens "draining" of the system following storms. The spring recession magnitude is typically a function of the last major storm of the wet season, which ranged from 15 to 262 cms and a rate of change (median daily percent decrease in flow per day) from 0.01 to 0.05 during baseline conditions.

Median dry-season baseflow in the mainstem of the LA River across all reporting nodes ranged between 0.12 and 3.5 cms. River discharge increased downstream of the three wastewater treatment plants, illustrating the contributions of discharges from the treatment plants (Fig. 4). On average, WRP discharge contributed the greatest proportion of flow during the summer months (June through August) (Fig. 4). Other sources of baseflow included groundwater upwelling and dry-weather stormdrain discharge (i.e., residential irrigation and car washing). Glendale Narrows (nodes LA14 through F57C) is a key area for aquatic life and recreation, but it is also one of the places where WRP discharge has a particularly large contribution (Fig. 4). Therefore, a reduction in WRP discharge could affect habitat and biodiversity, vital ecosystem function, and beneficial uses in this area (Cardinale et al., 2012; McCann, 2000; Tilman, 1999).

### 3.1.2. Suitability to support beneficial uses

Under current wastewater discharge conditions (annual average discharge of 1.91 cms), median baseflows in the Glendale Narrows are suitable for willow, an indicator of riparian habitat, and kayaking, which occurs in the summer months, across all baseline simulation years. In addition, flows can support cattail marsh in most years (67%) (Fig. 5). Current median baseflow conditions in the lower LA River are suitable for the migration of steelhead trout and green algae, which support wading shorebird foraging in the lower LA River mainstem (Fig. 5). It should be noted, however, that steelhead are not currently observed, likely due to other hydraulic, physical (e.g., dams), and water quality factors (e.g., temperature). Efforts are currently underway to more thoroughly examine the limiting factors for steelhead restoration in the watershed and develop a plan for channel modifications to improve suitability for steelhead in a 7.7 km reach of the river (Stillwater Sciences, 2020). Despite the suitability for all species of interest, current median baseflows are on the low end of the recommended flow ranges, particularly for cattail and kayaking in the Glendale Narrows (Fig. 5).

## 3.2. Wastewater reuse scenarios

### 3.2.1. Sensitivity of functional flow metrics

Across all wastewater reuse scenarios, the duration of the dry season increased by an average of 17 days, with a maximum of 22 days. The duration of wet-season baseflow decreased by an average of 16 days and the spring recession duration increased by an average of 41 days

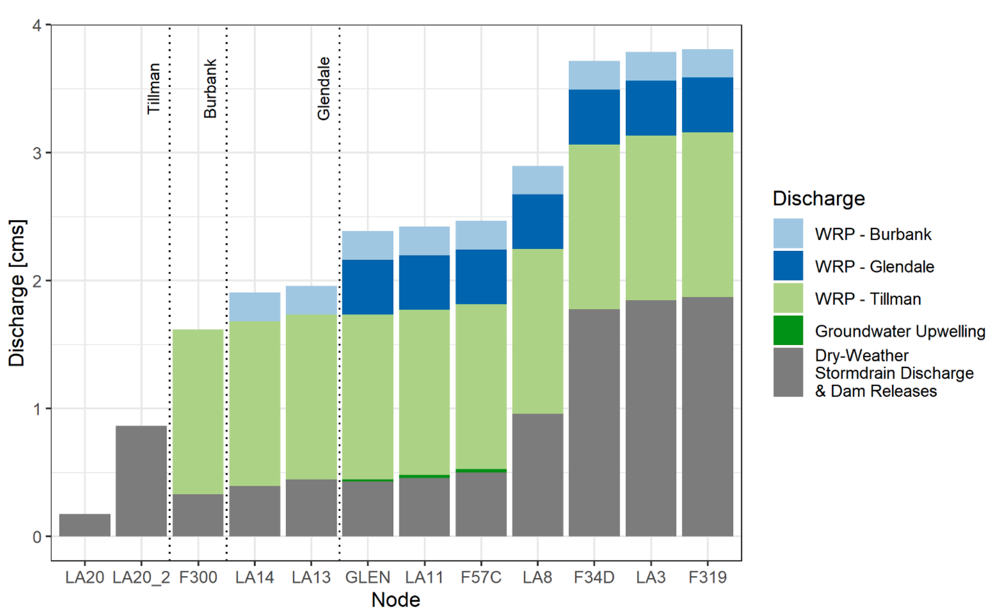


**Fig. 4.** The simulated relative contribution of WRP discharge to summer (June through August) median flows at each reporting node (water year 2011 to 2017). Dashed vertical lines represent the upstream inputs from the three wastewater treatment plants. Dry-weather stormdrain discharge includes industrial discharges and any flows running off the land surface that are not a result of a precipitation event. Nodes are ordered from left to right from upstream to downstream as shown in Fig. 1. Nodes within the Glendale Narrows are LA14, LA13, GLEN, LA11, and F57C.

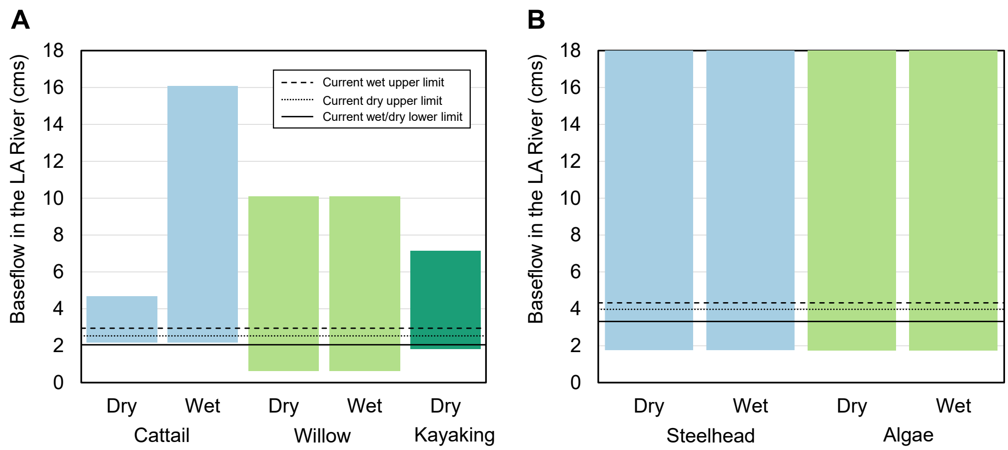


**Fig. 5.** Current baseflow conditions (10th to 90th percentile) and the ranges recommended to support beneficial uses in (A) the Glendale Narrows (GLEN) and (B) the lower LA River (LA3). Note that the upper limit for suitability of steelhead trout migration is 79.4 cms (beyond y-axis scale) and there is no reported baseflow upper limit for suitability of green algae. The dashed horizontal line is the 90th percentile wet-weather baseflow, the dotted horizontal line is the 90th percentile dry-weather baseflow, and the solid horizontal line is the 10th percentile baseflow (similar during dry and wet weather).

(maximum = 58 days). Of the calculated flow metrics, wet- and dry-season baseflow magnitude, spring recession rate of change (percent decreased in flow per day over spring recession duration), and spring recession duration were the most sensitive to changes in wastewater reuse. The most resilient metrics included peak flow durations and frequencies (Fig. 6). While the spring recession rate of change was sensitive to changes in WRP discharge on a percentage basis, the absolute rate of change values were extremely low (maximum absolute change is 5.9%, mean is 1.2%). Further, the fall and spring season metrics have minimal relevance for the ecology of the LA River, as previously discussed (Section 3.1.1).

The most consistent impacts of reduced WRP discharge were to baseflow, both during the dry and wet season, with decreases on average of 0.93 cms (33 cfs), which is an approximately 51–56% decrease from current conditions (Fig. 6). Wet-season baseflow metrics were slightly greater than dry-season metrics due to the contribution of residual stormdrain discharge following storm events. There are plans to install both distributed and centralized stormwater management systems throughout the watershed to replenish groundwater aquifers, reduce flood risk, and improve water quality (Geosyntec Consultants, 2015). This may have additional implications for both wet-season peak flows and baseflows.

Overall, we project that increases in wastewater reuse will result in a longer dry season, shorter wet season, and reduced baseflow. We concentrate on wet- and dry-season baseflow for the remainder of the analysis because baseflow is one of the most sensitive functional flow metrics to changes in wastewater reuse.

### *3.2.2. Suitability to support beneficial uses*

As wastewater reuse increases, the number of simulation years in

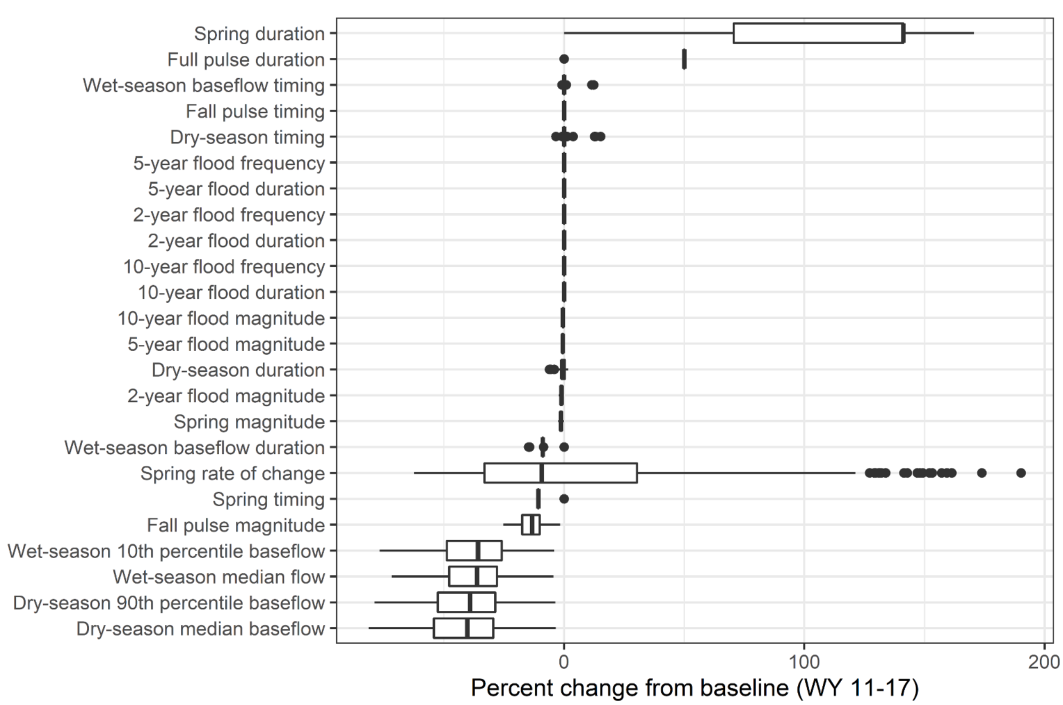


**Fig. 6.** Sensitivity of functional flow metrics to reductions in wastewater discharge relative to baseline conditions (water year 2011–17) at GLEN.

which baseflows fall within the recommended flow ranges for beneficial uses declines (Fig. 7). For example, with an average annual dry-season WRP discharge of 0.96 cms (50% of current WRP discharge), Glendale Narrows has flows that are suitable for willow but not for cattail or kayaking (Fig. 7) and the lower LA River has flows suitable for green algae and steelhead migration. However, the suitability for willow, green algae, and steelhead rapidly decreases when the average annual dry-season WRP discharge falls below about 0.6 cms (about 30% of current WRP discharge).

Wading shorebird (green algae) and freshwater marsh (cattail) habitat are representative of the wildlife habitat beneficial use in the LA River, which sustains both aquatic and terrestrial ecosystems by providing food resources, nurseries, and habitat for higher trophic level organisms including birds, amphibians, and invertebrates.

Wading shorebird habitat supports a large number of migratory and resident bird species (Cooper, 2006), some of which are threatened or endangered. Such species provide local and global benefits such as pest control, plant pollination, seed dispersal and are a food resource for other species (Martínez-Salinas et al., 2016; Michel et al., 2020; Sekercioglu, 2006). A reduction in wading shorebird population may lead to reduced pollination of plants, and therefore a reduction in plant populations (Anderson et al., 2011).

Freshwater marsh habitats comprise 25% of freshwater wetlands in the USA (Burton and Uzarski, 2009). As well as supporting a vast amount of biodiversity, freshwater marsh is known to filter nutrients and pollutants from runoff and surface water and has even been used in some areas to treat domestic and industrial wastewater (Bayley et al., 1985; Burton and Uzarski, 2009; Carlisle and Mulamoottil, 1991). Additionally, inland freshwater wetlands sequester and store carbon in soil, however, this ability may be hindered in anthropogenically disturbed areas (Nahlik and Fennessy, 2016) such as the LA River.

Less than 5% of natural wetlands (Greater Los Angeles County, 2012; Stein et al., 2014) remain in Los Angeles County, and nationwide bird populations have declined greatly (Rosenberg et al., 2019) over the past 50 years. The fact that these habitats currently exist in the highly urbanized LA River produces a unique opportunity for protection and management that should not be ignored.

### 3.3. Management implications

In addition to understanding the effects of wastewater reuse on beneficial uses, one of the key goals of this work was to inform future management decisions in the LA River watershed and other similar urban watersheds. To do this, flow-based sensitivity curves were developed for 18 nodes of management interest; curves are shown for the Glendale Narrows (GLEN) (Fig. 8) and lower LA River (LA3) (Fig. 9). The curves relate discharge from the water reclamation plants under various dry-weather stormdrain reduction scenarios to dry- and wet-season baseflow, which can then be related to beneficial use flow limits. The curves provide relationships between effluent discharge and streamflow at the 10th, 50th, and 90th percentiles based on the seven-year simulation record (Fig. 8 and Fig. 9). The sensitivity curve approach was developed in conjunction with basin stakeholders and a technical advisory group to ensure that the tools developed in this study could be used for decisions regarding the 1211 wastewater change petitions. This approach allows a potentially unlimited number of future reuse scenarios to be evaluated and therefore provides more utility than evaluating a finite number of discrete scenarios.

One potential use of the curves is to quantify the maximum amount of wastewater reuse that does not adversely affect existing beneficial uses based on aquatic habitat and recreation in the river. For example, during the dry season at Glendale Narrows, cattail is the most sensitive species to changes in WRP discharge; to maintain a median dry-season baseflow magnitude above the recommended range for cattail, WRP discharge should be maintained at 96% of the current discharge (1.84 cms). If instead, kayaking is prioritized over cattail, WRP discharge could potentially be reduced to about 77% of the current discharge (1.48 cms). If managers determine that only willow riparian habitat is a management priority, then WRP discharge could be reduced to 13% of the current discharge. There may also be flexibility in the timing of recycling during the day. For example, more water could be diverted for reuse at night to allow for sufficient flows for kayaking during the summer days. It is also important to note that kayaking is highly dependent on the channel morphology and flow ranges were developed from one representative cross-section at GLEN, which may be different than other locations in Glendale Narrows.

There is more flexibility for wastewater reuse in the Glendale Narrows during the wet season when discharge can be reduced to about 76% of the current rate without affecting cattail or willows (Fig. 8). Utilities within the basin could therefore prioritize wastewater reuse during wetter months. Note that these estimates are based on the median baseflow, but managers may want to use the 90th percentile band to be more conservative and provide additional opportunities for water reuse (Fig. 8).

The Lower LA River (LA3) is much less sensitive to changes in wastewater discharge than the Glendale Narrows (GLEN). Sensitivity curves suggest that discharge can be reduced to 2% of the current rate in the dry season and 6% in the wet season without impacting suitability for steelhead migration and green algae (Fig. 9). The greater flexibility for reuse in the lower LA River suggests that the Glendale Narrows

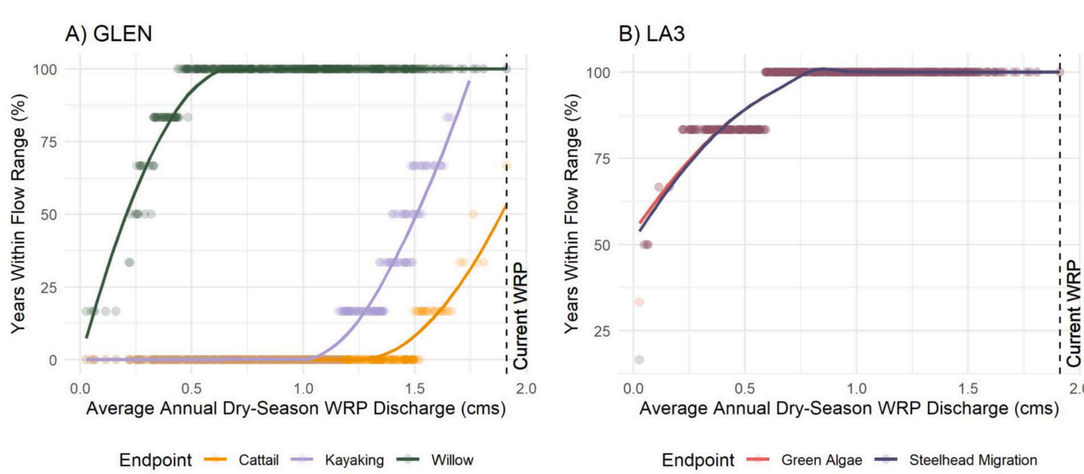


**Fig. 7.** Percentage of time the dry-season baseflow falls within the flow range for species and recreational uses at A) Glendale Narrows (GLEN) and B) lower LA River (LA3). Points represent results for each of the 500 wastewater discharge simulation scenarios. The curves shown were fit using Loess regression.

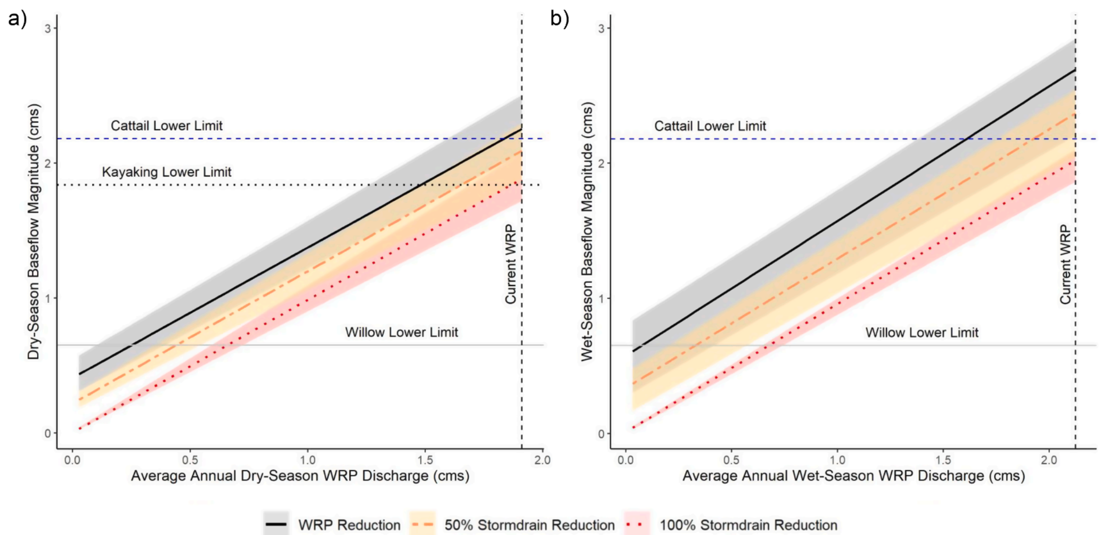


**Fig. 8.** Sensitivity curves at Glendale Narrows (GLEN) for dry-season (a) and wet-season (b) baseflow magnitude. The black line represents the median baseflow magnitude calculated across the simulation period. The yellow dashed line shows median baseflow under 50% dry-weather stormdrain reduction, and the red dotted line shows median baseflow under 100% dry-weather stormdrain reduction. The bands represent the 90th to 10th percentile of baseflow magnitude. The current average annual WRP discharge in the dry season and wet season are 1.91 and 2.12 cms, respectively.

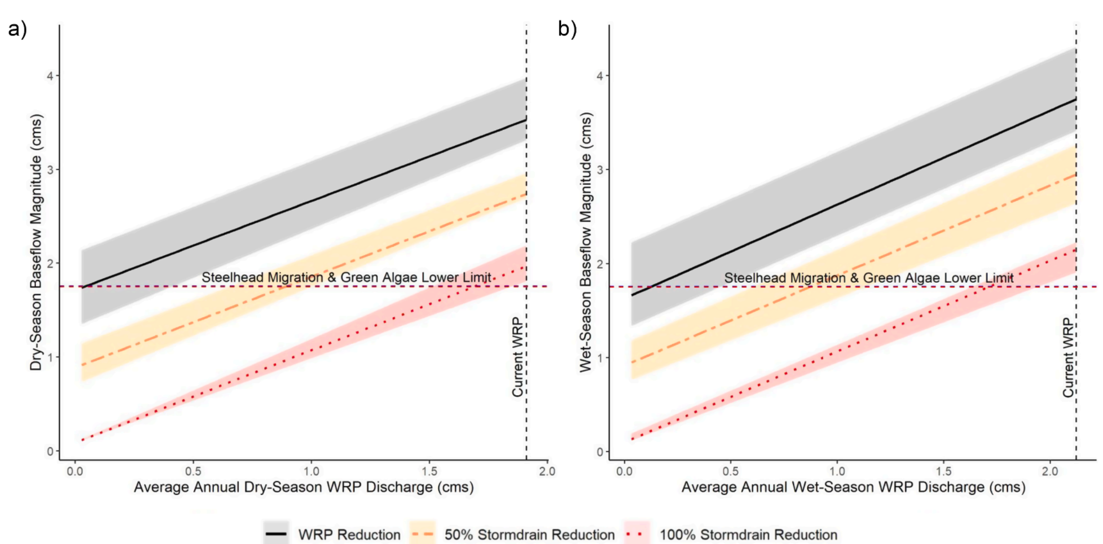


**Fig. 9.** Sensitivity curves at the lower LA River (LA3) for dry-season (a) and wet-season (b) baseflow magnitude. The black line represents the median baseflow magnitude calculated across the simulation period. The yellow dashed line shows median baseflow under 50% dry-weather stormdrain reduction, and the red dotted line shows median baseflow under 100% dry-weather stormdrain reduction. The bands represent the 90th to 10th percentile of baseflow magnitude. The current average annual WRP discharge in the dry season and wet season are 1.91 and 2.12 cms, respectively.

should be the focus of management efforts where a reduction in baseflow is more likely to impact beneficial uses. However, streamflow is not the only driver of habitat suitability. While current and future managed flows may be suitable for steelhead migration in the lower LA River, other factors like coarse substrate and pools and riffles that can serve as refugia are not present (U.S. Bureau of Reclamation, 2019). In addition, water quality parameters such as temperature may not be suitable (Abdi et al., 2022).

Results show that reductions in dry-weather stormdrain discharge would have a relatively large impact on both the Glendale Narrows and the lower LA River. In the Glendale Narrows, with no changes to WRP discharge, a 50% reduction in stormdrain discharge could impact the suitability of the habitat for cattail, and a 100% reduction of stormdrain discharge may impact the suitability of the habitat for cattail and kayaking (Fig. 8). In the lower LA River, with current WRP discharge, reduction of stormdrain discharge does not negatively affect steelhead migration or green algae growth. However, reductions in stormdrain discharge do have compounding effects with reductions in WRP discharge, thus illustrating the importance of considering the entire urban water cycle when making decisions on instream flows.

## 4. Conclusion

A functional flows approach was paired with a Monte Carlo simulation to estimate how wastewater reuse could impact beneficial uses in an effluent-dominated urban river. In Los Angeles, flow augmentation creates novel conditions that support both ecosystem services and societal benefits (e.g., recreation). Some future management scenarios can meet wastewater reuse goals and environmental flow patterns, primarily during the wet season when baseflows are typically greater and recreational boating activities are limited. We recommend that wastewater reuse in the LA River watershed be done in conjunction with channel restoration activities; baseflows in the river will be altered very quickly, which provides an opportunity for revitalization of the mainstem. Over time, the flood control capabilities of the channel may be reevaluated as the region plans for enhanced stormwater capture through distributed stormwater control measures, which will provide some flood protection.

We demonstrated that functional flow metrics can be joined with a suite of potential urban river disturbances or management scenarios to aid in future water planning and decision-making for environmental flows. In addition to potential changes in wastewater discharge, functional flow metrics could be paired with other management decisions such as increases in stormwater capture, reduction of dry weather urban baseflows, flow disturbances by climate change or wildfire, or restoration efforts. In future studies, we recommend that functional flow metrics be used with other habitat characteristics, such as hydraulic conditions (e.g., velocity and shear stress), water quality (e.g., temperature), and the life history needs for species of management concern. These sensitivity curves have advantages to the traditional approach of picking a handful of discrete scenarios to investigate. The developed approach can be applied to other urban watersheds where rivers must be managed for competing needs.

*CRediT authorship contribution statement*

**Jordyn M. Wolfand:** Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Formal analysis, Visualization. **Kristine T. Taniguchi-Quan:** Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Formal analysis, Visualization. **Reza Abdi:** Conceptualization, Methodology, Writing – review & editing. **Elizabeth Gallo:** Methodology, Investigation, Data curation, Writing – review & editing. **Katie Irving:** Conceptualization, Methodology, Writing – original draft. **Daniel Philippus:** Methodology, Investigation, Writing – review & editing. **Jennifer B. Rogers:** Conceptualization, Methodology, Writing – review & editing. **Eric D. Stein:** Conceptualization, Methodology, Writing – review & editing, Project administration, Funding acquisition. **Terri S. Hogue:** Conceptualization, Methodology, Writing – review & editing, Project administration, Funding acquisition.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.hydroa.2022.100124.

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