Application of regional flow-ecology relationships to inform watershed management decisions: Application of the ELOHA framework in the San Diego River watershed, California, USA

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Abstract
Relationships between changes in streamflow and changes in biological condition are important considerations for water resources management decisions. The Ecological Limits of Hydrologic Alteration (ELOHA) framework offers a way to protect stream health by managing flow conditions. We demonstrate application of a regionally derived ELOHA framework to inform stakeholder defined management challenges in the San Diego River Watershed in southern California, USA—a large semi-urbanized watershed that is undergoing land use changes. Using previously defined flow-ecology relationships based on benthic invertebrate community composition, we: (1) assess how future land use changes will affect flow conditions and impact biological endpoints in the watershed; (2) demonstrate how flow-ecology relationships can be used to prioritize regions of the watershed into various flow management classes that can inform future planning decisions; and (3) evaluate how two future management decisions (specifically, modification of reservoir operations and implementation of low impact development strategies to reduce stormwater runoff) will affect in-stream flow conditions in the watershed. Our study shows a successful transition of regionally derived flow targets to inform local decisions at a catchment or watershed scale, thereby avoiding the need to develop local flow-ecology relationships for every stream of interest (as would be required by other instream flow methods). Case studies are a critical bridge between the science of flow-ecology and real-world implementation, and this work illuminates an example of how to navigate technical and management challenges and provide road maps for broader applications by including local stakeholders in defining, interpreting, and implementing products of flow-ecology analyses.

KEYWORDS
benthic macroinvertebrates, ecohydrology, ELOHA, in-stream flows, stream health, water resources management

1 | INTRODUCTION

Flow regimes have been shown to fundamentally affect a broad suite of ecological processes that shape biological communities (Bunn & Arthington, 2002; Naiman et al., 2002; Novak et al., 2016; Poff & Zimmerman, 2010; Poff et al., 1997). Many studies have demonstrated that alterations of flow regime can be associated with changes in macroinvertebrate assemblages, which are used as key bioindicators for many regulatory and management programs globally (DeGasperi et al., 2009; Poff & Zimmerman, 2010; Pringle, 2000). Although an understanding of the relationship between flow alteration and ecological response exists (Poff et al., 2010), few studies have demonstrated how to develop regulatory or management objectives (or targets) based on these relationships or how targets can be applied to local management scenarios.

Quantitative and predictive relationships that predict change in flow relative to change in biological community composition is a critical step in using bioassessment indicators to establish measures of project performance or regulatory compliance. Various approaches have been used to develop relationships between flow characteristics and...
biological response. Examples include use of habitat suitability models that relate flow change to requisite habitats for target taxa (e.g., MesoHABSIM, Parasiewicz, 2009; and PHABSIM, Beecher, Caldwell, DeMond, Seiler, & Boessow, 2010); establishment of functional flow regimes to support species of management concern (McClain et al., 2014; Yarnell et al., 2015); and use of statistical ranges of sustainability based on unaltered hydrographs (Richter, Davis, Apse, & Konrad, 2011). Concepts from several of these approaches have been organized into the Ecological Limits of Hydrologic Alteration (ELOHA) framework (Poff et al., 2010). The ELOHA framework uses a variety of hydrologic and biologic tools to determine and implement environmental flows at the regional scale. Results of the ELOHA analysis can inform management decisions, such as release rates from dams, reservoirs or basins, diversion volumes for irrigation or water re-use, or flows associated with stream restoration. Because the ELOHA framework provides a way to assess the effect of flow alteration on the condition of biological communities (vs. individual taxa) on a regional basis, it is a useful approach for setting targets across a wide range of geographies and stream types where comprehensive detailed site-specific investigations are not practical. The ELOHA framework includes elements of stream classification, estimation of flow alteration and quantification of the relationship between flow alteration and changes in the biological community.

There have been several recent attempts to apply the ELOHA framework to develop flow targets for benthic invertebrates, fish, mussels, amphibians, and aquatic and riparian vegetation. Buchanan, Moltz, Haywood, Palmer, and Griggs (2013) completed the ELOHA approach in the mid-Atlantic region of the USA and was able to show relationships between changes in a subset of six flow metrics and six benthic invertebrate endpoints. This allowed the authors to recommend specific metrics that could be used for monitoring and assessment. McManamay, Orth, Dolloff, and Mathews (2013) applied ELOHA through a case study in North Carolina to assess the effect of a stream restoration on fish and riparian communities. Both Buchanan et al. (2013) and McManamay et al. (2013) noted that although the ELOHA framework could be used to relate hydrologic alteration to biological community condition, confounding factors (e.g., associations between flow alteration and water chemistry alteration) produced equivocal relationships with response of the biological communities. The Nature Conservancy has developed ecosystem flow recommendations for the Susquehanna River Basin (DePhilip & Moberg, 2010) and the upper Ohio River Basin (DePhilip & Moberg, 2013) using elements of the ELOHA framework in a qualitative manner that provide seasonally differentiated targets for different stream classes and multiple biological endpoints (e.g., fish, mussels, amphibians, and vegetation). Solans and Jalón (2016) used a series of flow alteration-ecological response curves to develop environmental flow standards for the Ebro River Basin in the Iberian Peninsula. Most recently, Mazor, May, Sengupta, McCune, and Stein (in press) capitalized on extensive regional biomonitoring data and a set of regional hydrologic models developed by Sengupta et al. (in press) to develop flow-ecology relationships for southern California based on benthic macroinvertebrate communities as a measure of stream health.

Most previous studies have focused on using the ELOHA framework for establishing flow targets and thresholds using relationships between changes in flow and changes in biological condition. There are far fewer examples of the application of ecologically derived flow targets (or thresholds) to inform actual management decisions. The main place where flow-targets have been implemented to inform management actions is in the Juanita Creek Watershed in Washington State, USA (King County, 2012). The Juanita Creek study evaluated the effectiveness of seven potential stormwater mitigation scenarios at achieving biologically relevant flow targets using a calibrated Hydrological Simulation Program-Fortran model; a single scenario was identified which would accomplish the stated watershed goals. To our knowledge, none of the previous cases studies attempted to apply regionally-derived flow-ecology relationships (such as those developed for southern California) to inform decisions at the watershed scale.

The goal of this project is to demonstrate a process for applying regionally derived flow-ecology relationships, developed by Mazor et al. (in press), at a watershed scale to inform in-stream flow management targets/decisions. Applying regional relationships at a watershed level also serves as a test for validity of the relationships and can illuminate discrepancies that are not always obvious at a regional scale. Active stakeholder participation is integral to this demonstration because they help define issues and interpret the utility of the recommendations resulting from the analysis. The stakeholders for this study were selected based on their regulatory and management responsibilities in the watershed and on their expressed desire to incorporate results of the flow-ecology analysis into water resource or water quality management decisions. The stakeholder workgroup identified three questions important to informing local in-stream flow management decisions:

1. How has current flow alteration affected biological conditions in the watershed, and how will future land-use changes affect flow conditions and impact biological endpoints in the San Diego River watershed? That is, how do current hydrologic conditions compare to those expected under a 2050 land use scenario?
2. How can flow-ecology relationships be used to assign regions of the watershed into various flow management classes, with appropriate priorities for future planning decisions?
3. What are the biological implications of two future management decisions that will affect in-stream flow conditions?
   a. reduced discharge from Santee Lakes Reservoir due to increased capture and storage to meet demand for reclaimed water
   b. reducing effective imperviousness, and implementing stormwater capture strategies in a developed portion of the watershed

2 METHODS

2.1 Study area

We conducted the case study in the 440 square miles (1,140 km²) San Diego River, a large, partially urbanized watershed in southern California (Figure 1). Although the headwaters are largely undeveloped, extensive portions of the river have been impounded to provide
drinking water storage and flood control to more than half a million residents both within and outside the catchment boundaries. Important hydrologic resources in the watershed include five water storage reservoirs, a large groundwater aquifer, extensive riparian habitat, and coastal wetlands. The San Diego River watershed is a valuable case study because it includes a range of stream types, including reference (as defined by Ode et al., 2016) and highly impacted reaches; it is affected by several types of hydrologic alteration, including urban runoff, flood control, and reservoir management; it is relatively data-rich, benefiting from years of ambient and targeted monitoring programs (e.g., Mazor, 2015); and there is an active and engaged stakeholder workgroup that is willing to participate in the demonstration project.

2.2 | Regional ELOHA (flow-ecology) analysis

The local management questions mentioned above were addressed using regional flow-ecology relationships conducted for southern California that relate changes in flow to changes in stream health (Mazor et al., in press). Stream health was assessed using the California Stream Condition Index (CSCI; Mazor et al., 2016), a statewide index of benthic macroinvertebrate community composition. Hydrologic alteration was assessed based on a series of hydrologic metrics, which were shown to have strong statistical and ecological relationships with the CSCI (Mazor et al., in press; Stein et al., 2017). Flow metrics were also selected to ensure representation of different components of the flow regime (e.g., duration and magnitude) and different climate conditions (e.g., wet vs. dry vs. average years). Because we lack measured flow data for both current and historic conditions at most bioassessment sites, both were estimated using watershed models.

Regional benthic macroinvertebrate data were obtained from the southern California regional bioassessment program (Mazor, 2015), using standard protocols described by Ode (2007). A total of 572 wadeable stream sites were sampled between 2008 and 2014, most of which were sampled under a probabilistic sample design. These sites were randomly distributed across the entire stream network using a spatially balanced generalized random-tessellation design that ensured representation across all natural and anthropogenic gradients in the region (Stevens & Olsen, 2004). Data from sites sampled at non-probabilistic locations were also included in the analysis.

Benthic macroinvertebrate data was used to calculate the CSCI (Mazor et al., 2016). The CSCI is a predictive index that compares observed taxa and metrics to values expected under reference conditions based on site-specific landscape-scale environmental variables, such as watershed area, geology, and climate. It includes two components: a ratio of observed-to-expected taxa (O/E) and a predictive multi-metric index made up of six metrics related to ecological structure and function of the benthic macroinvertebrate assemblage. Because the CSCI and all its components are based on site-specific reference expectations, scores are minimally influenced by major natural gradients. Therefore, CSCI scores, by definition, compare existing to reference conditions and can be used as a measure of biological alteration (delta B) under anthropogenic stress. CSCI scores and all components were classified as indicating "intact" or "altered" condition, using the normal approximation of the 10th percentile of CSCI reference calibration scores as a threshold (Mazor et al., 2016). For the CSCI, this equates to a score of 0.79 (where 1 is the reference expectation) as the threshold between biologically intact and altered.

This study took advantage of regional hydrologic and biological response models developed for Southern California (Figure 2; described in detail in Sengupta et al., in press and Mazor et al., in press). Hydrologic alteration was modeled at the 572 bioassessment sites using an ensemble of 26 HEC-HMS models developed as part of the regional flow ecology analysis (Sengupta et al., in press). HEC-HMS provides the ability to produce a continuous time series of estimated flow through parameterization of relatively small number of variables in the model (HEC-HMS manual version 4.1, Xuefeng & Steinman, 2009, ACOE, 2000, Schraffenberg and Fleming, 2006). One of the 26 models can be applied to produce a daily flow time series for every
bioassessment site based on basin properties draining to that site. This obviates the need to develop a unique model for every site. Inputs used to develop and parameterize the models are grouped in three categories: (1) watershed-specific data (e.g., area and imperviousness), (2) site-specific data (e.g., observed flow and precipitation), and (3) model-specific parameters (e.g., initial loss and number of reservoirs).

Each model was sequentially calibrated for four criteria: visual hydrograph match, Nash–Sutcliffe efficiency (NSE), percent low flow days, and Richards–Baker Index of flashiness. These calibration endpoints were selected based on relevance for supporting the instream biological communities (Konrad & Booth, 2005; Morley & Karr, 2002). Models were calibrated for a 3-year period from 2005 to 2007 reflecting a wet, average, and dry year and were then validated for temporal and spatial performance. For temporal validation, the calibrated models were run for years outside of the calibration period, mostly for the period 2007–2010 and matched with the observed flow data. In all cases, model performance (as measured by NSE) during the validation period was within 15% of performance during the calibration period.

To evaluate spatial performance, we applied statistical “jackknifing” to all calibrated gauges. In this analysis, each modeled gauge is treated as an “ungauged” site, and the remaining 25 models are used to predict flows at that site. The models were fitted to the “ungauged” site by inputting watershed-specific data and model-specific parameters, but without changes to the model-specific parameters. These simulations were run for the 3-year calibration period. Approximately 75% of the sites had an acceptable NSE value higher than 0.5 (Moriasi et al., 2007). A final validation was performed by comparing modeled output to measured flow at 16 bioassessment sites with nearby flow gauges (but not included in the model development).

To assign a validated flow model to an ungauged site, cluster analysis was used to identify groups of hydrologically similar calibration

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**FIGURE 2** Workflow to establish targets for hydrologic alteration and create an index
gazes. Subsequently, a random forest model was developed to predict cluster membership of novel sites based on watershed characteristics. This random forest model was used to estimate the statistical proximity between an ungaged site and each calibration gauge. The most proximal gauge was then assigned to the ungaged site.

Precipitation data for each of the 572 sites were estimated from a network of 206 regional rain gauges by inverse distance weighting interpolation. The models were then run with 23 years of precipitation data (1992 to 2013) to generate hourly discharge time series data. Outputs from 6 years representing different climate conditions (i.e., two wet, two average, and two dry years) were selected at random for further analyses; restricting analyses to 6 years was required because many sites lacked precipitation data that could be used to run the models for more years. Hourly hydrographs were then aggregated to daily discharge, and a suite of flow metrics was calculated for both current and historic (i.e., "reference") conditions (Konrad, Brasher, & May, 2008; Table S2). These metrics (selected because of their presumed biological and managerial relevance) were then assigned to one of 5 metric classes: duration, frequency, magnitude, timing, and variability. For each metric-precipitation combination, hydrologic alteration was characterized as differences between metric values calculated under current and historic condition. "Historic condition" was estimated by adjusting model parameters to reflect undeveloped watershed conditions. For many catchments, the historical flows are zero for extended periods of time skewing estimates of certain magnitude metrics, in such cases, we used a minimal flow of 0.0283 cms (1 cfs).

Hydrologic metrics were evaluated for wet, dry, average and a multi-year (6 years) analysis defined as the overall climatic conditions resulting in 121 metric-precipitation condition combinations. The flow metrics calibrated and validated well, but the validation results vary by metric category. Magnitude metrics had the highest \( r^2 \) values under all conditions with most values ranging between 0.34 and 0.99. Metric-precipitation combinations that validated poorly (i.e., \( r^2 < 0.25 \)) at the calibration sites were excluded from further analysis. We predicted metrics for the dry and overall climatic conditions better than the average and the wet years. This approach assumes that hydrologic alteration is a long-term disturbance that degrades biological conditions at a site, and that hydrologic alteration is easier to detect and relate to biological responses under certain climatic conditions; therefore, poor biological conditions observed in one climate condition can be related to hydrologic alteration measured in other climate conditions.

Thresholds for each flow metric were set by evaluating biological responses to gradients of hydrologic alteration, as described in Mazor et al. (in press). The CSCI and its components were used to assess biological responses, and each flow metric-precipitation condition combination that validated with an \( r^2 > 0.25 \) was used to assess hydrologic alteration. Logistic regression models were used to predict the likelihood of good biological conditions being observed at increasing levels of hydrologic alteration. The glm function in R, with a binominal error distribution and a logit link function (R Core Team, 2016) was used to create models. Because stressors unrelated to hydrologic alteration may inflate these likelihoods, we divided the predictions by the likelihood of poor biology where hydrology was unaltered. Increasing and decreasing gradients of hydrologic alteration were evaluated independently, and non-significant (i.e., \( p < 0.05 \)) models were excluded from further analysis. Targets for each metric were then set at the level of flow alteration where the rescaled likelihood was 0.5, corresponding to a 50\% reduction in the likelihood of observing good biological conditions. Because targets were set for multiple biological response variables, only the most conservative (i.e., closest to zero) target was selected for further analysis; in general, the most conservative target was associated with the multi-metric index component of the CSCI.

We used boosted regression tree (BRT) analysis to rank hydrologic metrics based on their relationships with biological condition for the full suite of 121 flow metric-precipitation condition combinations. BRT models were run using the gbm package in R (R Core Team, 2016; Ridgeway, 2015) and with specific code from Elith, Leathwick, and Hastie (2008). Each BRT model was developed with the following parameter settings: we used a bag fraction of 0.50, a learning rate of 0.0005 for developing our models, and a tree complexity of 5. Variable relative importance (VRI) was calculated using formulae developed by Friedman (2001) and implemented in the gbm package to estimate the relative influence of each flow metric. Calculations of VRI are based on the number of times a variable is selected for splitting, weighted by the squared improvement to the models as a result of each split, averaged over all trees. VRI values were ranked within in each biotic response model from 1 to 121, with 1 being the best rank. Ranks were then averaged across all nine biological response variables. Metric-precipitation condition combinations were selected for further analysis if they had at least one target supported by the logistic regression analysis, described previously. Within a metric, only the best-ranked precipitation condition was selected for further analysis.

To select a subset of metrics to use in a hydrologic alteration index, up to two metrics were selected in order of average rank from each metric class (i.e., duration, magnitude, variability, and frequency), as long as the average rank was better than the median average rank. The subset of flow metrics was re-run in new BRTs in order to evaluate their relationship with biological response variables. Metrics were scored 0 if they met targets, 1 if they failed targets, and 2 if they failed by more than twice the target value. Sites that scored 2 or more were designated as hydrologically altered. To examine the relationship between the index and biological response variables, the index score was then plotted against each response variable. A smoothed fit from general additive models was added by using the default settings of the geom_smooth function in the ggplot2 package in R (R Core Team, 2016; Wickham, 2009).

An objective of the regional flow-ecology analysis was to identify a subset of priority flow metrics that can be used to inform management actions. Metrics were first prioritized based on how strongly they were associated with changes in biological community composition (as indicated by change in CSCI score). VRI was calculated from the BRT output using formulae developed by Friedman (2001) and implemented in the gbm package to estimate the relative influence of each flow metric. We selected the highest ranked metrics that represented different elements of the hydrograph, that is, flow magnitude, duration, variability, and frequency, allowing for selection of up to two
metrics for each hydrograph element (Table 2). Metrics were further prioritized based on the following criteria:

- Differentiate hydrologic condition at reference sites vs. altered sites
- Have the strongest relationship to biological condition based on BRT analysis and can produce a hypothesized ecological response
- Can be modeled under both current and reference conditions with a high level of confidence
- Are amenable to management actions and are expected to respond in predictable ways to deliberate changes in flow conditions
- Have minimal redundancy with other metrics; the goal is to select metrics that represent different components of the hydrograph (e.g., magnitude vs. duration)

### 2.3 Application of regional flow-ecology (ELOHA) relationships to guide watershed management actions

Current and future hydrologic condition for the San Diego River watershed were evaluated for 52 distinct catchments defined by bioassessment locations (29 sites), major stream nodes, and other sites of interest (Figure 1). For each catchment, we simulated current and reference hydrology using the most appropriate of the regional HEC-HMS models (as described previously) and calculated hydrologic alteration (delta H) as the difference in the flow metrics between current and reference conditions. The hydrologic alteration index presented in Mazor et al. (in press) was calculated for each site. This index is based on seven metrics selected for the highest influence on biological endpoints. Each metric is scored a zero if the site met the target (based on 50% probability of meeting the biological threshold), a 1 if it exceeded the flow metric target, and a 2 if it exceeded the flow metric target by more than twice the target value as described previously. Metric scores were then summed to create an overall score for the index of hydrologic alteration for better translation to management communities. Index scores of 0 were in category “A” (unaltered or minimally altered), 1 to 2 in category “B” (low alteration), 3 to 6 in category “C” (moderate alteration), and 7 to 14 in category “D” (severely altered).

Flow management classes were assigned to each of the 29 bioassessment sites (Table 1), based on their biological and hydrological status. Hydrological classes A and B were considered hydrologically intact when assigning sites to different management classes. Biological status was inferred using CSCI scores: Sites with scores greater than 0.79 were designated as biologically intact, and sites with lower scores were designated as biologically altered (Mazor et al., 2016). Sites with good hydrologic and biologic conditions were put into a “protection” class; the good conditions at these sites should be protected from further degradation. Sites with poor hydrological conditions and good biological conditions were put into a “monitoring” class; these sites may be resilient to stressors related to hydrologic alteration, but factors related to this apparent resiliency should be monitored to ensure that they continue to support biological health. Sites in poor hydrological and biological condition were put into a “flow management” class; these sites should undergo a causal assessment to determine if flow management is likely to improve biological condition or if other constraints (e.g., channelization) may limit the ability of a stream to respond to improved flows. Sites with good hydrological condition and poor biological condition were put into an “other management” class. For these sites, we examined other monitoring data collected concurrently with the bioassessments to provide preliminary assessment of the likelihood that flow management would improve biological condition (Table 1). Potential additional causes of biological alteration were evaluated for all locations where the CSCI was less than 0.79 based on additional stressor data such as water chemistry and physical habitat assessments that are routinely collected as part of the regional ambient monitoring programs (Mazor, 2015).

Success of the case study was dependent on active stakeholder participation. A diverse group of stakeholders representing local municipalities, water districts, a land conservancy, a non-governmental organization, water quality regulatory agencies, the U.S. Forest Service as the upper watershed landowner and a local consulting firm were invited to identify core issues in the watershed. The stakeholder workgroup met monthly over an eight-month period and engaged in all aspects of the project including detailed scoping, assisting in modeling and analysis, and interpretation and refinement of findings. This intimate participation was key to developing products that would be acceptable for incorporation into future management decisions.

Regional flow-ecology relationships were used to address three critical management questions identified through the stakeholder process:

1. How has current flow alteration affected biological conditions in the watershed and how will future land use changes affect flow

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**TABLE 1** Management categories defined based on combination of hydrologic and biologic alteration. Good hydrologic condition is defined as hydrologic classes A and B, poor hydrologic condition is defined as classes C and D. A CSCI score of 0.79 is used as the threshold between good and poor biological condition.

<table>
<thead>
<tr>
<th>Poor hydrologic condition</th>
<th>Good hydrologic condition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Poor biology (CSCI &lt;0.79)</strong></td>
<td><strong>Flow Management:</strong> Evaluate hydrologic alteration among other stressors. Determine relative importance of flow management for improving biological condition, relative to other stressors.</td>
</tr>
<tr>
<td><strong>Good biology (CSCI &gt;0.79)</strong></td>
<td><strong>Monitor:</strong> Communities may be resilient to flow alteration. Continue to monitor for factors that may reduce resilience.</td>
</tr>
</tbody>
</table>

CSCI, California Stream Condition Index.
conditions and impact biological endpoints in the San Diego River watershed?

2. How can flow–ecology relationships be used to prioritize regions of the watershed into various flow management classes that can inform future planning decisions?

3. How can flow–ecology relationships be used to inform proposed changes to discharges and stormwater capture practices in the watershed?

For each question, we explored alternative future scenarios based on different management decisions. To address the first question, we explored the effect of extensive residential development by 2050 throughout the upper watershed in areas that are currently undeveloped. For the second question, we assessed the effect of reduced reservoir discharge from Santee Lake to Sycamore Creek, a tributary to the San Diego River. This is an expected scenario with increasing effluent recycling. For the third question, we modeled the impact of stormwater control measures in Alvarado Creek, a heavily urbanized sub-catchment of the San Diego River. Flow metrics were calculated under current conditions (i.e., 50% imperviousness), as well as under conditions of reduced effective impervious area (specifically, 2%, 5%, 10%, and 25% effective imperviousness). In addition, metrics were calculated assuming that imperviousness is not reduced, but instead a detention basin is built to capture the 85th percentile of a 24-hr storm.

For each scenario, the most appropriate hydrologic model was selected using the model selection tool (described previously) and was used to simulate both current and future streamflow conditions based on the proposed management actions. The projected hydrologic change for each scenario (and each alternative within a scenario) was evaluated relative to the flow–ecology relationships and thresholds developed by the regional analysis. To aid in management interpretation of the results of the scenario analysis, the regional thresholds, which are expressed as change in the metric value, were converted to the actual target values of flow metrics for each specific situation evaluated in the case study. The results of this analysis were used to develop flow management recommendations for each scenario.

### RESULTS

The metric selection process identified seven priority flow metrics and associated thresholds of biological response (Table 2). The importance of the seven priority flow metrics varied by climatic condition (e.g., wet vs. dry vs. average rainfall years), with some metrics only being important during certain precipitation conditions. When evaluating the effect of management scenarios on the seven flow metrics, we focus on the climatic condition most important for each metric.

#### 3.1 Effect of future land-use change on hydrologic condition

To address the question, “how has current flow alteration affected biological conditions in the watershed and how will future land-use changes affect flow conditions and impact biological endpoints in the San Diego River watershed?”, we compared the current overall hydrologic condition to the expected future condition based on 2050 SanGIS land-use projections, assuming no installation of stormwater control device or low impact development features.

Under current conditions, 17 of the 52 catchments (33%) scored in the worst two categories of hydrologic alteration, while 35 of 52 (67%) scored in the two least hydrologically altered categories A and B. There appears to be a spatial gradient of hydrologic condition in the watershed, with the most hydrologically intact areas in the upper watershed, where much of the land is in public ownership and/or there is currently little urban development. Catchments in the poorest hydrologic condition are concentrated in the lower watershed where most of the current development exists. These areas are also downstream of all the reservoirs in the watershed (Figure 3).

We also evaluated all 35 metrics to provide additional information about the type of hydrologic alteration occurring in each catchment. Catchments that are hydrologically unaltered based on the overall assessment (Classes A and B) generally had only three to four individual metrics (out of 35 total) that were considered altered. This suggests that the targeted set of metrics (based on our screening filters described above) is representative of overall hydrologic condition. The most commonly exceeded metrics range across nearly all categories:

### Table 2 Priority hydrologic metrics and associated thresholds used in the regional flow-ecology relationships. Metrics are grouped by the hydrograph component they represent. Thresholds are expressed as the change in metric value (delta H) associated with poor biological condition (CSCI <0.79). Metric effects on biology were typically strongest during either average, wet, or dry rainfall years, or all years combined (overall). NT = no threshold established.

<table>
<thead>
<tr>
<th>Hydrograph component</th>
<th>Metric</th>
<th>Metric definition</th>
<th>Critical precipitation condition</th>
<th>Decreasing threshold</th>
<th>Increasing threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration</td>
<td>NoDisturb (days)</td>
<td>Median annual longest number of consecutive days that flow is between the low and high flow threshold</td>
<td>Average</td>
<td>-64</td>
<td>NT</td>
</tr>
<tr>
<td></td>
<td>HighDur (days/event)</td>
<td>Median annual longest number of consecutive days that flow was greater than the high flow threshold</td>
<td>Wet</td>
<td>-3</td>
<td>24</td>
</tr>
<tr>
<td>Magnitude</td>
<td>MaxMonthQ (m³/s)</td>
<td>Maximum mean monthly streamflow</td>
<td>Wet</td>
<td>NT</td>
<td>1.5</td>
</tr>
<tr>
<td>Variability</td>
<td>Q99 (m³/s)</td>
<td>99th percentile of daily streamflow</td>
<td>Wet</td>
<td>-0.01</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>Richards-Baker index of stream flashiness</td>
<td>QmaxIDR (m³/s)</td>
<td>Interdecile range of flow</td>
<td>Overall</td>
<td>-5</td>
</tr>
<tr>
<td>Frequency</td>
<td>HighNum (events/year)</td>
<td>Median annual number of events that flow was greater than high flow threshold</td>
<td>Dry</td>
<td>NT</td>
<td>3</td>
</tr>
</tbody>
</table>
duration metrics (e.g., high duration), magnitude metrics (e.g., Q95), frequency metrics (e.g., HighNum), and variability metrics (e.g., RBI). This suggests that when hydrologic alteration occurs, it tends to affect most aspects of runoff hydrographs rather than preferentially influencing certain hydrologic elements. Hydrologic condition was generally related to catchment imperviousness (Figure 4). In most cases, severe hydrologic alteration was associated with total impervious cover greater than 5%. In all cases, hydrologically unaltered catchments (Classes A and B) had less than 5% total impervious cover, often only 1–2%.

Under 2050 land use projections, hydrologic conditions of the watershed are expected to degrade because of increased urban development and imperviousness, mainly in the middle portion of the watershed (Figure 5). Mid watershed catchments, around existing reservoirs, are expected to degrade the most in association with future land use changes, with several catchments going from Class A to Class C. Little change is expected in the upper watershed because many of the catchments in the upper watershed are hydrologically unaltered, in public ownership and hydrologic conditions are expected to remain unaltered into the future. Most of the lower watershed is already in poor hydrologic condition and is expected to remain that way in 2050, unless substantial hydrological management and/or remediation measures are implemented. Overall, we predict that 16% of the total watershed will undergo alteration under the 2050 land use scenario. Most hydrologic changes are expected to occur in catchments less than 200 square miles (518 km²), which tend to respond quickly to flow alterations. Future land use changes were associated with sufficient hydrologic alteration to affect all seven metrics that contribute to the overall hydrologic rating (Table 3). We expect the flow regime will be flashier with an overall increase in number and duration of high flow events and a net increase in overall annual flow. This more energetic environment will likely increase disturbance of microhabitats and lead to an overall simplification of instream physical habitat. It is important to note that future conditions were modeled using the same precipitation values as the current and historical scenarios because reliable downscaled future precipitation values are not available. Furthermore, the future conditions assumed no stormwater control devices, low impact development or hydromodification management, because we have no information on where/how these will be installed in the future. Therefore, the results of the 2050 analysis should be considered a worst-case scenario under current climate conditions.
3.2 Prioritization of areas for various management actions

To address the question, "How can flow-ecology relationships be used to prioritize regions of the watershed into various flow management classes that can inform future planning decisions?" we compared the overall hydrologic condition scores to the CSCI scores at the 29 locations in the watershed where bioassessment has previously occurred.

Most upper watershed sites were considered intact, with unaltered hydrology, and therefore a high priority for protection. Candidate areas for flow management were focused in the lower portion of the watershed where both hydrology and biological condition were altered.

Considering both the flow management zones and information available on water quality, habitat, and channel condition from ambient survey data allowed us to provide specific management recommendations that can be prioritized for each location (Figure 6). Using response thresholds for chemistry, nutrients, and habitat that have been established through the southern California regional monitoring program (Mazor, 2015), we estimate that flow alteration is the primary factor affecting biology at only 3 of the 13 biologically degraded sites in the lower watershed. At all other sites, flow management should be coupled with habitat or water quality remediation to improve biological conditions. The lower watershed was largely in poor biological condition with altered
hydrology, making flow management a good option to consider for improving watershed health. However, many of the sites in this category had highly developed floodplains or concrete-lined channels, and all lower watershed sites had poor water quality. Therefore, flow management should always be considered in conjunction with other forms of management that address water-quality impacts and alterations to physical habitat.

3.3 | Evaluation of management scenarios

The stakeholder workgroup prioritized two future management scenarios for evaluation. Each of them represents potential actions that will affect in-stream flow conditions, and in turn may affect biological condition.

### 3.3.1 | Scenario 1. Lower discharge from Santee Lakes Reservoir

The Santee Lakes Reservoir receives treated wastewater from Padre Dam Municipal Water District’s Ray Stoyer Water Recycling Facility. The lake releases the treated effluent to Sycamore Creek (which also receives water from a small rain-fed discharge from the lake). The future management scenario involves eliminating discharge of treated wastewater into the lakes and diverting it for reuse to help meet increased demands for recycled water. This will be associated with a proportional decrease in discharge from Santee Lakes Reservoir to Sycamore Creek (because there is less need to create capacity in the lakes); the rain-fed discharge will continue to be released to the creek.

Simulations of future scenarios using HEC-HMS indicate that the flow regime will continue to have natural variability, with lower magnitude of flows under the future management scenario relative to current conditions (Figure 7). Current conditions at Sycamore Creek are altered mainly in terms of the duration of elevated flow conditions (e.g., HighDur and NoDisturb). This reflects discharge from Santee Reservoir that elevates downstream high flow conditions associated with seasonal releases to create capacity in the reservoir. The balance of the priority flow metrics are currently meeting targets (Table 4). Under future scenarios, many high flow metrics are expected to improve in response to the removal of discharges from the reservoir. In contrast, the remaining metrics will remain at or slightly below the targets associated with healthy biological conditions. Failure to achieve these targets under future conditions likely reflects the effects of ongoing urban runoff, which will not be affected by changes in the reservoir operation. Overall the hydrologic condition in Sycamore Creek will improve under high flow conditions, but is likely to remain in degraded hydrologic and biological condition, even if discharges from Santee Lakes are eliminated following the proposed management scenario.

![Management Recommendations](image)

**TABLE 3** Changes in hydrologic metrics between current and 2050 land use scenarios for 52 catchments in the San Diego River watershed expressed as both percent of total catchments and percent of total watershed areas.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Percent of catchments</th>
<th>Percent of area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NC</td>
<td>Inc</td>
</tr>
<tr>
<td>QmaxIDR</td>
<td>46</td>
<td>54</td>
</tr>
<tr>
<td>NoDisturb</td>
<td>64</td>
<td>36</td>
</tr>
<tr>
<td>Q99</td>
<td>75</td>
<td>15</td>
</tr>
<tr>
<td>HighNum</td>
<td>64</td>
<td>36</td>
</tr>
<tr>
<td>RBI</td>
<td>67</td>
<td>33</td>
</tr>
<tr>
<td>HighDur</td>
<td>73</td>
<td>8</td>
</tr>
<tr>
<td>MaxMonthQ</td>
<td>85</td>
<td>15</td>
</tr>
</tbody>
</table>

Dec, decrease in the metric value; Inc, increase in the metric value; NC, no change is observed for a metric.

![FIGURE 6](image) Recommended management actions for all sites where bioassessment has occurred. Recommendation are based on both flow-ecology information and available data on habitat and water quality obtained through the local regional monitoring program.
Based on the results of the scenario analysis and stakeholder feedback, we made the following specific management recommendations for the Santee Reservoir/Sycamore Creek scenario, which are derived from the regional flow targets:

- **NoDisturb** = Maintain an average low flow between 0 and 0.02 cms (0.7 cfs) for a minimum of 119 days during the dry season.
- **HighDur** = Maintain flow greater than 0.02 cms (0.7 cfs) for between 25 and 52 days per year.
- **MaxMonthQ** = Maintain mean monthly flows below 0.1 cms (3.5 cfs).
- **Q99** = Storm flows (or high flow events) should be between 0.03 cms (1 cfs) and 1.1 cms (39 cfs).
- **HighNum** = Ensure less than four high flow events per year with a flow greater than 0.02 cms (0.7 cfs).

Variability metrics do not lend themselves to directed management actions; therefore, we have not provided recommendations for RBI or QmaxIDR. Instead these flow metrics should be used to evaluate the effectiveness of actions taken in response to the other metrics.

### 3.3.2 Scenario 2. Impact of disconnecting imperviousness and implementing stormwater retention facilities in an urbanized catchment

Alvarado Creek catchment is located in the downstream portion of the San Diego River watershed. At an area of 36 km$^2$ and 50% total impervious cover, it is a heavily urbanized and hydrologically altered reach. We tested two scenarios in this sub-catchment: (1) effect of reducing imperviousness via diffused infiltration, and (2) implementing stormwater retention facilities that can capture 85th percentile of a 24-hr rain event.

Reducing effective imperviousness (i.e., the amount of impervious cover that is hydrologically connected to the stream) decreases the extent of hydrologic alteration in the creek. However, flow metrics do not drop below levels associated with healthy biological communities until the total imperviousness is at or below 5% (Table 5). For most metrics, there is a 50% likelihood of meeting flow targets at 10% impervious cover, 66% likelihood at 5% impervious cover and an 80% likelihood of meeting flow targets at 2% impervious cover. Above 10% impervious cover, the likelihood of achieving flow targets declines by 15%. This is consistent with previous results that 5% impervious cover appears to be an important level or maintaining biologically protective levels of flow. For the 85th percentile of a 24-hr storm event, based on a precipitation isohyetal developed for San Diego River watershed, any storm event with less than or equal to 1.9 cm (0.75 inches) is assumed to be 100% captured by the retention structures. This level of capture translates to ability to meet flow targets for some metrics (e.g., NoDisturb and MaxMonthQ), but not others. The 85th percentile capture may reduce flood peaks beyond a level which is associated with healthy biological communities.

Based on the results of the scenario analysis and stakeholder feedback, we made the following specific management recommendations for the Alvarado Creek scenario, which are derived from the regional flow targets:

- **NoDisturb** = Maintain an average low flow between 0 and 0.01 cms (0.4 cfs) for a minimum of 119 days during the dry season.
- **HighDur** = Maintain flow greater than 0.01 cms (0.4 cfs) for between 27 and 56 days per year.

### TABLE 4

Current and expected future hydrologic metric values in Sycamore Creek downstream of Santee Reservoir. The table presents site-specific targets that have been calculated based on the regional threshold values.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value Target</th>
<th>Value</th>
<th>Unit</th>
<th>Current</th>
<th>Future</th>
<th>Lower</th>
<th>Higher</th>
</tr>
</thead>
<tbody>
<tr>
<td>NoDisturb</td>
<td>Days</td>
<td></td>
<td></td>
<td>31</td>
<td>122</td>
<td>119</td>
<td>NT</td>
</tr>
<tr>
<td>HighDur</td>
<td>Days/event</td>
<td></td>
<td></td>
<td>212</td>
<td>28</td>
<td>25.1</td>
<td>52.2</td>
</tr>
<tr>
<td>MaxMonthQ</td>
<td>cms</td>
<td></td>
<td></td>
<td>0.1</td>
<td>0.0</td>
<td>NT</td>
<td>0.1</td>
</tr>
<tr>
<td>Q99</td>
<td>cms</td>
<td></td>
<td></td>
<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
<td>1.1</td>
</tr>
<tr>
<td>HighNum</td>
<td>Events/year</td>
<td></td>
<td></td>
<td>1</td>
<td>4</td>
<td>NT</td>
<td>4</td>
</tr>
<tr>
<td>RBI</td>
<td>Unitless</td>
<td></td>
<td></td>
<td>0.0</td>
<td>0.9</td>
<td>NT</td>
<td>0.3</td>
</tr>
</tbody>
</table>

NT, no target assigned.

Green cells represent conditions where flow targets would be met; yellow cells represent conditions where flow would be the same as the target value.

---

**FIGURE 7** Modeled daily discharge under current and future scenarios at Sycamore Creek. The blue line represents the current scenario (which includes effluent discharge), and the orange line represents a future scenario where effluent is reused and not discharged into the creek.
TABLE 5  | Response of key metrics to changes in total impervious cover and 85% runoff capture. The table presents site-specific targets that have been calculated based on the regional threshold values.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Unit</th>
<th>2%</th>
<th>5%</th>
<th>10%</th>
<th>25%</th>
<th>50%</th>
<th>85th % storm</th>
<th>Lower</th>
<th>Higher</th>
</tr>
</thead>
<tbody>
<tr>
<td>NoDisturb</td>
<td>Days</td>
<td>32</td>
<td>32</td>
<td>32</td>
<td>32</td>
<td>31.5</td>
<td>32</td>
<td>119</td>
<td>NT</td>
</tr>
<tr>
<td>HighDur</td>
<td>Days/event</td>
<td>35.5</td>
<td>34</td>
<td>32.5</td>
<td>24</td>
<td>9</td>
<td>8</td>
<td>27</td>
<td>56</td>
</tr>
<tr>
<td>MaxMonthQ</td>
<td>cms</td>
<td>0.31</td>
<td>0.35</td>
<td>0.41</td>
<td>0.59</td>
<td>0.88</td>
<td>0.53</td>
<td>NT</td>
<td>0.66</td>
</tr>
<tr>
<td>Q99</td>
<td>cms</td>
<td>0.19</td>
<td>0.45</td>
<td>0.89</td>
<td>2.04</td>
<td>4.04</td>
<td>2.64</td>
<td>0.2</td>
<td>0.67</td>
</tr>
<tr>
<td>HighNum</td>
<td>Events/year</td>
<td>23.5</td>
<td>22.5</td>
<td>23.5</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>NT</td>
<td>4</td>
</tr>
<tr>
<td>RBI</td>
<td>Unitless</td>
<td>0.22</td>
<td>0.47</td>
<td>0.75</td>
<td>1.15</td>
<td>1.4</td>
<td>1.39</td>
<td>NT</td>
<td>0.23</td>
</tr>
</tbody>
</table>

NT, no target assigned.

Green cells represent conditions where flow targets would be met.

- MaxMonthQ = Maintain mean monthly flows below 0.66 cms (23 cfs)
- Q99 = Storm flows (or high flow events) should be between 0.2 (7 cfs) and 0.66 cms (23 cfs)
- HighNum = Ensure less than four high flow events per year with a flow greater than 0.01 cms (4 cfs)

4  | DISCUSSION

Local case studies are a critical step in transitioning regionally derived flow targets into implementation (Poff et al., 2010). Case studies provide a "proof of concept" and a "road map" for broader implementation to support management decisions. They also provide a mechanism to iteratively refine flow targets using additional monitoring data, professional judgement, and consideration of all complementary and competing factors necessary to develop targets that can address often divergent interests. The San Diego River case study provides an illustration of how watershed stakeholders are critical partners in the process. Resultant flow standards provide a starting point for developing agreed upon, adaptive flow management programs that can protect intact waterbodies and restore those that are currently impacted. Future efforts can build on the experiences from this case study and continue to refine the process of developing flow targets that are scientifically defensible, practical (i.e., can lead to management actions), and consistent with local stakeholder needs.

4.1  | Regional flow targets can support management decisions at local scales

This study demonstrates the value of regionally derived flow-ecology relationships for a variety of local management decisions. We were able to demonstrate the utility of applying the flow-ecology relationships to inform management for both point source and non-point source management scenarios. For both the reservoir management scenario and the stormwater runoff management scenario, we were able to determine a range at which hydrologic management may facilitate recovery of degraded biological communities. The stakeholder-guided process allowed us to identify technical and practical benefits and challenges associated with the approach that can inform future implementation efforts.

Regionally derived understandings of flow-ecology relationships can support a variety of important management decisions at local levels. We were able to prioritize management actions at numerous sites, identify watersheds vulnerable to planned developments, select effective stormwater control measures, and evaluate the impacts of changes in reservoir operations. The ability to apply regionally derived flow thresholds to inform local decisions is a major benefit of the ELOHA approach. Regionally derived targets reduce the need to develop local flow-ecology relationships for every site of interest, as might be the case in more traditional instream flow methods (Beecher et al., 2010; McClain et al., 2014). The tools developed through the regional analysis provided readily transferable tools for local stakeholders to produce measures of hydrologic change for any location of interest and to explore how those values would change under different land use or management scenarios. This had the dual benefit of allowing for robust analysis and providing a vehicle for stakeholder engagement in setting management priorities related to in-stream flow, an important cornerstone of the ELOHA approach.

Stakeholder engagement in the underlying science and the rationale behind how regional flow targets were developed was key to local implementation of the regional flow-ecology relationships. Investing in educating a diverse group of stakeholders that included regulatory agencies, municipalities, water agencies, non-governmental organizations, and researchers ensured a broad perspective in the deliberations, fostered creative solutions to the complex challenges of flow management, and increased the likelihood of developing balanced recommendations. For example, the map of hydrologic management categories was identified as one of the most useful products for planning purposes because it allows stakeholders to prioritize areas for protection and for flow management. This analysis has since been expanded to support similar prioritization at the regional scale.

4.2  | Local applications provide insight into developing regional targets

Local applications provide valuable lessons and feedback for ecologists and hydrologists working at regional scales. In particular, they highlight the types of sites where regional models work best, and where they are prone to misinterpretation. For example, the case study made us aware that several sites in the San Diego watershed were likely intermittent or ephemeral under historic conditions. These sites had
many metric values at or near zero under historic conditions, and even slight increases in impervious surfaces were interpreted as severe hydrologic alteration. Consequently, regionally derived flow targets could not be met under most reasonable management scenarios (DeGasperi et al., 2009). Analysis at the local scale helped us recognize these anomalously sensitive sites, leading us to interpret alteration differently at historically perennial (e.g., Sycamore Creek) and intermittent (e.g., Alvarado Creek) sites. Ultimately, new or modified metrics may need to be developed to accommodate establishing flow management targets appropriate for naturally intermittent or ephemeral streams.

Application of the regional flow-ecology relationships to local management scenarios revealed several complications associated with the formulations of certain commonly used metrics (Solans & Jalon, 2016). Many duration metrics are calculated based on frequency or duration of flows above or below a benchmark derived from a long-term flow record. For example, the HighNum metric is calculated as the number of flow events over the 90th percentile of daily flow. This formulation may not be suitable for evaluating hydrologic change, because the benchmark shifts along with other parts of the hydrograph, thereby obscuring hydrologic impacts. This problem is not easily apparent in regional analyses due to the large sample size, and is clearest when applied to a specific site, as in the present study. We recommend that future analysis use a constant, unshifting benchmark based on historical conditions when estimating thresholds for duration metrics based on thresholds of high- or low-flow events.

The degree of hydrologic modification was correlated with impervious cover. We found that hydrologic alteration generally occurred in catchments with greater than 5% total impervious cover (with most alteration occurring above 2% total imperviousness), which is similar to other studies that have shown that channel degradation due to hydromodification occurs at relatively low levels of imperviousness (Hawley and Bledsoe, 2011; Hawley, Bledsoe, Stein, & Haines, 2012; Vietz et al., 2016). However, we also found that local factors mediate the way stream organisms respond to flow. For example, local reach morphology influences how flow alteration can affect the duration of wetting of bars and localized velocity zones, which has consequences for instream fauna (Kath et al., 2016; Kennedy et al., 2016). Hydrologic change at the local (small) scale may be ecologically important but is likely not affected by managing for the flow metrics we identified, and may be difficult to address through any regionally derived flow management framework. Channelization and other habitat constraints at certain sites in this study underscore the shortcomings of prescribing flow management to improve biological condition without considering local factors. Furthermore, although our regional flow criteria were developed in consideration of wet, dry, and average climatic cycles, they likely do not account for longer term climate patterns and extreme episodic events that may be important for establishing and maintaining resilient instream habitats. This deficiency was highlighted by McManamay et al. (2013), who found that results of ELOHA analysis cannot necessarily be used in a predictive manner because biological communities may respond to other factors not included in the flow-ecology analysis, such as changes in substrate associated with infrequent events, such as catastrophic floods or fires. Moreover, they note that temporal resolution of most case studies does not coincide with the temporal period of data underlying ELOHA relationships. For example, streams may respond to episodic events and patterns operating on decadal time scales. Development of flow metrics that capture these interannual and longer term hydrologic patterns should be a priority for future analysis.

4.3 Case studies can advance the science of flow-ecology

Development and application of the regional flow-ecology relationships through this local case study provided an opportunity to explore and refine several elements of the ELOHA approach. The seven priority flow metrics we selected included two measures of magnitude, two of duration, two measures of variability, and one of frequency. This combination ensures that most elements of the hydrograph will be addressed through flow management. The selected metrics have hypothesized relationships that affect macroinvertebrate communities, allowing us to communicate their ecological relevance to managers and local stakeholders (Poff et al., 2006; Table 6). They are also amenable to management and minimize redundancy between metrics (Table 7). Interestingly, our metrics are similar to those identified by DeGasperi et al. (2009) who found that decreases in macroinvertebrate indices in urbanizing watersheds in the Puget Sound area of Washington were associated with changes to the number and duration of high and low flow events, and flow flashiness. One important difference is that low flow metrics were not identified as priority management targets in our study even though previous studies have identified the relationship between low flow and invertebrate community richness (Stubbleington, Wood, & Boulton, 2009). This may be an anomaly due to the difficulty in modeling low flow conditions with HEC-HMS and/or that other flow-ecology relationships ranked higher based on our statistical modeling and prioritization criteria. It is important to note that hypothesized relationships for both this study and other similar studies were derived through statistical analysis of regional bioassessment data sets. Additional mechanistic studies will be important to validate these relationships and confirm their ecological relevancy. As such studies are completed, they can be used to refine flow management targets based on improved understanding of the flow-ecology relationships.

Use of the predictive CSCI index in our regional flow-ecology analysis as opposed to a traditional (i.e., non-predictive) index of biotic integrity provided a consistent and straightforward measure of biological change, which has been a challenge for past ELOHA applications (e.g., McManamay et al., 2013). Developing the regional flow-ecology relationships and applying them at the local scale would not have been possible without the regional bioassessment data and the existence of the predictive scoring tool (Mazor et al., 2016). Large regional data sets provide sufficient sample size to develop statistically meaningful flow-ecology relationships in spite of the inherent "noise" in the data associated with other co-occurring factors that interact with flow to affect biological community condition (Solans & Jalon, 2016). The predictive scoring tool is a measure of biological condition relative to expected reference (historical) conditions and thus provides a readily available measure of biological change (delta B) at every site. The
• **NoDisturb (days)** is the median annual longest number of consecutive days that flow is between the low (Q10) and the high flow (Q90) threshold. Disturbance changes the bed shear stress and affects sediment transport. While an increase in the number of no-disturbance days does not have a high negative impact on the stream health, a decrease in the number of days is significant. Under urbanization scenarios we usually see a decrease in the number of no-disturbance days.

• **HighDur** is the median annual longest number of days the flows were greater than upper threshold (Q90). This metric only has a lower threshold and a corresponding lower target. In terms of management, as long as the metric value is higher than the lower target, the stream is not failing the metric. Both the duration metrics require several years of data.

• **MaxMonthQ (cms)** is the maximum mean of the monthly flows. The MaxMonthQ has an upper threshold and associated target but no lower target. The management goal is to ensure that the metric values are below the upper target value. In cases of urbanization, we see a rapid increase in the MaxMonthQ.

• **Q99 (cms)** is a high flow threshold, or the top 1% of the flow and has upper and lower bound targets in cms. The management goal is to maintain the metric values within this range. In cases of urbanization, we see a rapid increase in the Q99 values.

• **RBI** describes the oscillation in flows (or discharge) relative to the total flows (Baker, Richards, Loftus, & Kramer, 2004). This flashiness metric usually increases with urbanization which impacts the runoff patterns. However, the flashiness might decrease in case there are dams or steady controlled releases from reservoirs which dampen the natural flashiness of the hydrograph. The metric has an upper target, which implies that an extreme flashy stream is unhealthy for the biological communities, and the management goals should focus on keeping the RBI scores below the upper target value.

• **Qmax IDR** measures variability as the difference between the high flow threshold (Q90) and low flow threshold (Q10) divided by the 50th percentile flow (Q50). A higher value implies increasing variability, which is typically the case in streams without hydrologic regulation.

• **HighNum** is the frequency metric which estimates the number of events where the flow is higher than Q90 threshold. This metric has an upper target which implies that the management should focus on maintaining high flow events to a number less than the upper target.

### TABLE 6 Hypothetical biological responses to alterations in six selected flow metrics

<table>
<thead>
<tr>
<th>Metric</th>
<th>Description</th>
<th>Implications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NoDisturb</strong></td>
<td>Decrease: Times between spates and droughts are too short to support the expected abundance and diversity of long-lived taxa (e.g., semivoltine insects). Flood-dependent reproducers (e.g., cottonwoods) have fewer opportunities to establish. Good recolonists (drifters, strong fliers, and exiters) will flourish. Increase: Long-lived taxa are able to out-compete taxa that reproduce quickly or recolonize.</td>
<td></td>
</tr>
<tr>
<td><strong>HighDur</strong></td>
<td>Decrease: Reduced time with floodplain access, reducing floodplain subsidies to fish and inverts, and diminishing time for riparian seedlings to establish. Increase: Desiccation resistance is less useful. More opportunities for aerial colonization (good fliers)</td>
<td></td>
</tr>
<tr>
<td><strong>HighNum</strong></td>
<td>Decrease: Fewer flushing flows. Allows more clogging of substrate and encroachment of macrophytes. Reduction of spawning gravels for fish. Deposition will fill pools. Greater accumulation of algae may lead to increased grazing. Increase: More scouring flows. More incision and bank erosion, leading to mortality of riparian vegetation. Direct mortality of long-lived organisms may eliminate semivoltine taxa.</td>
<td></td>
</tr>
<tr>
<td><strong>Q99 and MaxMonthQ</strong></td>
<td>Decrease: Reduces size of flushing flows, allowing more clogging of substrate and encroachment of macrophytes. Reduction of spawning gravels for fish. Deposition will fill pools. Greater accumulation of algae may lead to increased grazing. More desiccation-resistant taxa. More predation, and more predation-resistant (armored, or quick reproducers) taxa. Increase: Greater scour, leading to incision and bank erosion. Riparian vegetation mortality will increase, both through bank failure and lowering of the water table. Greater flushing of leaf litter will lead to a decline in shredders.</td>
<td></td>
</tr>
<tr>
<td><strong>Qmax IDR</strong></td>
<td>Decrease: Greater similarity between high and low flows will result in more stable channel morphology, with less bank erosion, leading to a reduction of large woody debris entering the stream. Access to the floodplain will be reduced, limiting growth of fish and amphibians that take advantage of this resource. Increase: Increased differences between high and low flows may destabilize channels, leading to greater bank erosion or incision, affecting the growth or survival of riparian vegetation. The consequent loss of riparian vegetation may decrease shading and leaf-litter input to the stream, shifting the trophic structure from an allochthonous system to an autochthonous one.</td>
<td></td>
</tr>
<tr>
<td><strong>RBI</strong></td>
<td>Decrease: Reduced flashiness decreases the frequency of mortality events, allowing the proliferation of long-lived semivoltine taxa. Increase: Increased flashiness favors short-lived, multi-voltine taxa and good dispersers that can recover quickly after frequent flooding events.</td>
<td></td>
</tr>
</tbody>
</table>

availability of similar data and tools should be a major consideration for other efforts interested in developing regional approaches. Our reliance on developing flow targets based on the response of a single community assumes that the macroinvertebrate community reflects overall ecological condition. Although this is not a totally unreasonable assumption, we recognize that different components of the stream ecosystem may be affected differently by changes in various components of the hydrograph. Kath et al. (2016) demonstrated that basing targets on ecological traits within the macroinvertebrate community, such as dispersal ability, can be more diagnostic than relationships based solely on community composition. Other ELOHA efforts have attempted to address this issue by developing flow–ecology relationships for multiple communities (e.g., fish, vegetation, and mussels) and recommending targets around protection of each (DePhilip & Moberg, 2013). This approach is more robust, but complicates development of management measures that can address all biological endpoints. Ultimately, such an approach is likely less parsimonious for regulatory applications.

These issues reinforce the concept that flow-ecology relationships should be used as one line of evidence in coordination with other
factors/considerations when establishing stream management prescriptions and targets. In particular, many watersheds are subject to complex regulatory and management systems that involve combinations of new and retrofit facilities aimed at reducing runoff and retaining flows for infiltration and reuse. The regional flow targets established by Mazor et al. in press and applied in this case study can be an important consideration in designing and implementing integrated watershed management plans aimed at meeting both short and long term objectives.

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REFERENCES


Parasiewicz, P. (2009). Habitat time series analysis to define flow augmentation strategy for the Quinebaug River, Connecticut and
Massachusetts, USA. River Research and Applications. Published online in Wiley InterScience (www.interscience.wiley.com) https://doi.org/10.1002/rra.1066


**SUPPORTING INFORMATION**

Additional Supporting Information may be found online in the supporting information tab for this article.

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