

Risk-Decision Framework for Evaluating Vulnerability of Streams to Hydrologic Alteration



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SOUTHERN CALIFORNIA COASTAL WATER RESEARCH PROJECT

Technical Report 1322

Risk-Decision Framework for Evaluating Vulnerability of Streams to Hydrologic Alteration

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EXECUTIVE SUMMARY

Hydrologic alteration is a pervasive issue across southern California and is a primary factor that contributes to the degradation of biological communities (Poff and Zimmerman 2010). The 2009-2013 regional bioassessment survey completed by the Stormwater Monitoring Coalition concluded that altered hydrology, largely as a result of stream channel modification, was the greatest risk factor associated with poor biological condition in southern California streams (Mazor 2015). Given its pervasiveness, there is a need to evaluate the extent and magnitude of hydrologic alteration over large regions to support planning, regulatory and management decisions. Moreover, we lack tools to readily evaluate risk of hydrologic alteration relative to future changes in climate, land use, and water use practices and to assess potential effects on stream ecological health. This project developed tools to help stakeholders and the Regional Board evaluate the potential severity of effects of proposed projects that have the potential to alter flows and to inform decisions regarding stream protection, restoration, and management in light of anticipated flow alteration.

The main objectives of this study were to:

- 1) Evaluate the extent of current hydrologic alteration at the stream reach scale across the entire San Diego Regional Board jurisdiction (RB9 region)
- 2) Evaluate biologically relevant hydrologic degradation to streams in the RB9 region
- 3) Develop a risk-decision framework and tool to evaluate proposed projects or alternative future scenarios in terms of their likelihood to alter hydrology to a level that may impair aquatic life uses

This report describes the methods, findings, and data products of the study to answer the three study objectives.

Hydrologic alteration

This study evaluated contemporary hydrology across a suite of 24 functional flow metrics that describe the magnitude, timing, frequency, and duration of functional flow components identified as important for California streams (Yarnell et al. 2020). Our aim was to assess current hydrologic alteration by estimating functional flow metric (FFM) changes from reference to current conditions for river segments in the San Diego region, including ungauged segments, using a machine learning (Random Forest, RF) algorithm. The algorithm establishes the relationship of climate and catchment descriptors, including descriptors of the physical environment and human impacts, to the change in functional flow metrics from the expected

reference condition (Figure ES1). We built the RF models using gage data from across California, to ensure sufficient training data, and applied the RF model to NHD stream segments in the study region.

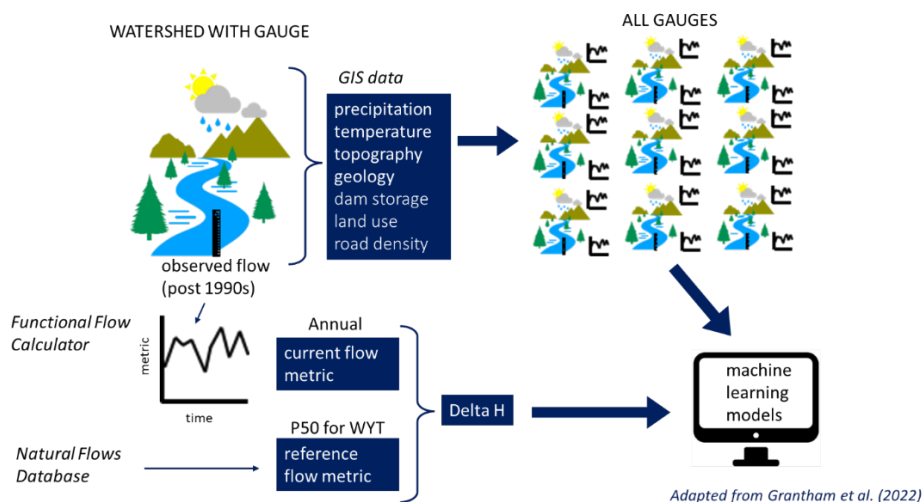


Figure ES1. Overview of random forest modeling approach. Note that WYT means water year type (wet, moderate, or dry).

To evaluate model performance, we split the gage dataset into 70% of sites for model training and 30% of sites for independent model testing (testing sites) and excluded 10 outlier gages from training and testing. Models for metrics of flow magnitude across all functional flow components performed satisfactory or greater. All other metrics that had unsatisfactory model performance were excluded from the study.

Relative hydrologic alteration was mapped across the study region. Dry-season baseflow magnitude tended to be augmented across the region with higher levels of augmentation in the more urbanized areas (Figure ES2). Of the modeled stream reaches, 90% had at least some level of flow augmentation in the dry season.

Biologically relevant flow alteration: Benthic communities

Biologically relevant flow alteration was assessed by identifying reaches where flow alteration is sufficient to be associated with a decline in biological condition as indicated by the standard statewide biological indices, the California Stream Condition Index (CSCI, Mazor et al. 2016) for benthic invertebrates and the Algal Stream Condition Index (ASCI, Theroux et al. 2020) for benthic algae. We analyzed reaches based on biotic alteration by relating biotic indices and FFM (outputs from the random forest models) using revised flow ecology curves from Irving et al. (2022).

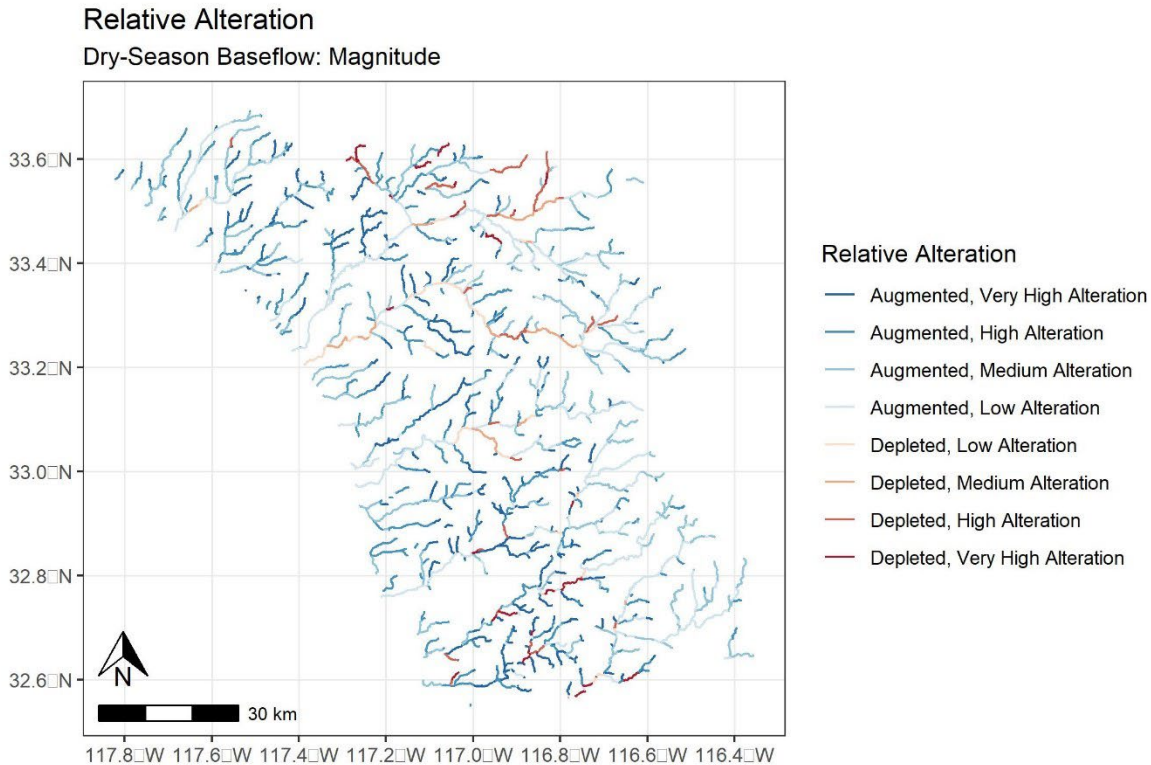


Figure ES2. Relative alteration map for dry-season baseflow magnitude.

Predicted probabilities of supporting healthy biology for the study area are summarized in Tables ES1a and ES1b (using a threshold of 0.7 probability). CSCI was the slightly more sensitive index of the two, with all FFM s having a larger number of reaches with < 0.7 probability of achieving a healthy CSCI score, compared to ASCI. Fall pulse magnitude was the most sensitive FFM for ASCI, with 476 (22.05%) reaches with a < 0.7 probability of a healthy score (Figure ES3B). The least sensitive CSCI FFM was 10-year flood magnitude with 126 (5.95%) of reaches with a < 0.7 probability of a healthy score (Figure ES3C). Note that there was not enough data to develop the flow-ecology relationship for positive peak metrics (i.e., bioassessment sites that had larger peak magnitudes compared to reference expectations). Therefore, reaches with augmented peak magnitudes were classed as “indeterminate”. This was the case for CSCI 10-year flood magnitude (Figure ES3C) and ASCI 2-year flood magnitude (Figure ES3F). For CSCI 10-year flood magnitude, 1,109 (52.41%) reaches were indeterminate while 461 (21.79%) were indeterminate for ASCI 2-year flood magnitude (which was also the most sensitive metrics for ASCI with 326 (15.41%) reaches with a < 0.7 probability). The metrics with the highest number of reaches with a probability ≥ 0.7 of a healthy score for CSCI and ASCI were: wet season

median magnitude with 1,846 (87.24%) reaches and spring recession magnitude with 2,074 (98.02%) reaches, respectively.

Table ES1a. Probability of NHD reaches achieving a healthy CSCI score based on chosen flow metric.

Flow Metric	Reaches with ≥ 0.7 Probability	Reaches with < 0.7 Probability	Indeterminate Reaches
Dry-season baseflow magnitude	1,755 (82.94%)	361 (17.06%)	NA
10-year flood magnitude	881 (41.64%)	126 (5.95%)	1,109 (52.41%)
Fall pulse magnitude	1,640 (77.50%)	476 (22.50%)	NA
Wet-season median magnitude	1,846 (87.24%)	270 (12.76%)	NA

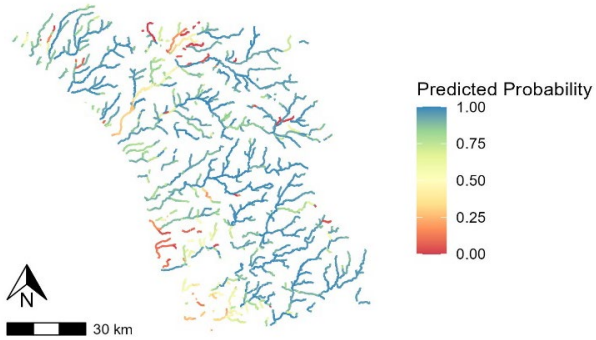
Table ES1b. Probability of NHD reaches achieving a healthy ASCI score based on chosen flow metric.

Flow Metric	Reaches with ≥ 0.7 Probability	Reaches with < 0.7 Probability	Indeterminate Reaches
Dry-season baseflow magnitude	2,012 (95.09%)	104 (4.91 %)	NA
2-year flood magnitude	1,329 (62.81%)	326 (15.41%)	461 (21.79%)
Spring recession magnitude	2,074 (98.02%)	42 (1.98%)	NA
Wet-season median magnitude	1,918 (90.64%)	198 (9.36%)	NA

A

CSCI

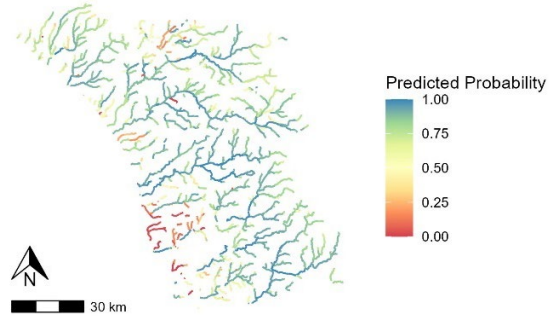
Predicted Current Probability
Dry-Season Baseflow Magnitude (cfs)



B

CSCI

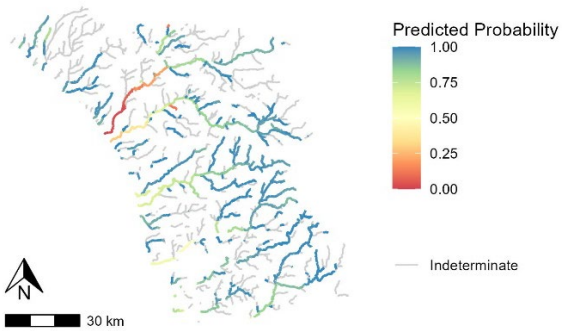
Predicted Current Probability
Fall Pulse Flow Magnitude (cfs)



C

CSCI

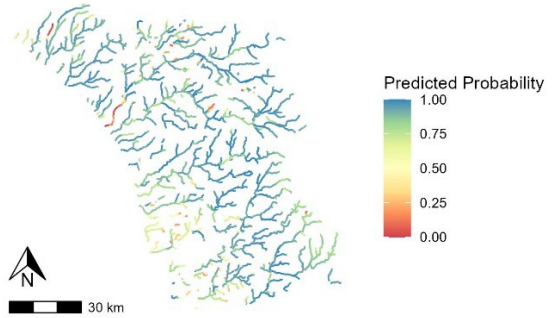
Predicted Current Probability
Peak Flow Magnitude (10-year flood, cfs)



D

CSCI

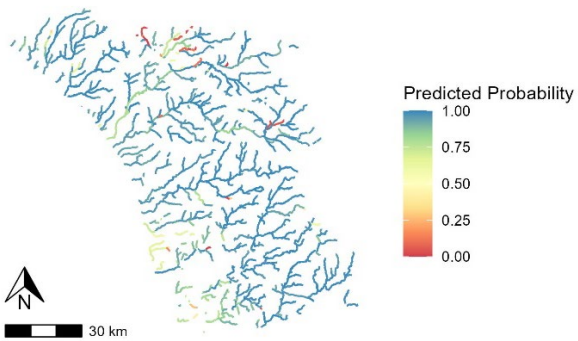
Predicted Current Probability
Wet-Season Median Magnitude (cfs)



E

ASCI

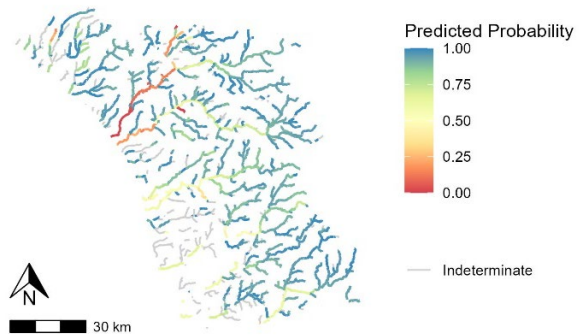
Predicted Current Probability
Dry-Season Baseflow Magnitude (cfs)



F

ASCI

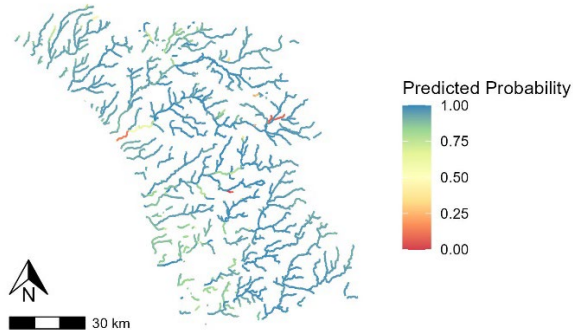
Predicted Current Probability
Peak Flow Magnitude (2-year flood, cfs)



G

ASCI

Predicted Current Probability
Spring Recession Flow Magnitude (cfs)



H

ASCI

Predicted Current Probability
Wet-Season Median Magnitude (cfs)

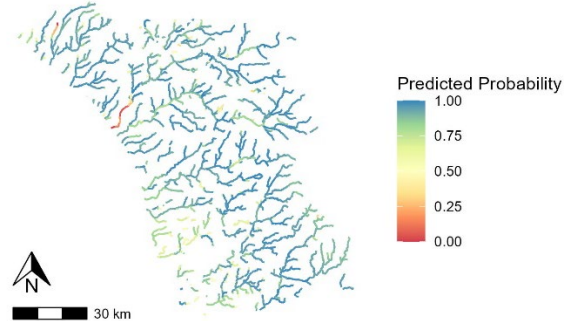


Figure ES3. Predicted probability of achieving a healthy ASCI and CSCI score per chosen FFM metrics over the RB9 region.

The relative hydrologic alteration maps and the biologically relevant flow alteration based on CSCI and ASCI can be viewed at:

https://sccwrp.sharepoint.com/:f:/s/SDHydroVulnerabilityAssessment/Em6WdRTtc1dKqTspiyWve20B9kvAA3z_7xEbHARQs7cQwg?e=fVbve3.

Biologically relevant flow alteration: Focal species

The arroyo toad (*Anaxyrus californicus*) was selected as our focal species of management concern for this study in accordance with our technical advisory group (TAG). The toad is native and endemic to Southern California and listed as endangered under the Endangered Species Act (Jennings and Hayes 1994; Sweet 1992; U.S. Fish and Wildlife Service (USFWS) 1994).

We applied a Species Distribution Model to predict the probability of occurrence of arroyo toad to habitat-related variables describing flow, catchment, and landscape characteristics. The model is based on the previously developed landscape model from Treglia et al. (2015), with updated physical and biological data as well as the addition of functional flow metrics modeled in this study. We predicted the probability of toad occurrence by applying a classification Random Forest (RF) model that produces a probability of achieving a binary outcome (i.e., presence, absence) by relating toad observations to associated physical conditions in geographical space.

The mean probability, of 10 model iterations, of toad occurrence is shown in Figure ES4. High probabilities are mostly evident in low gradient and more natural locations such as San Mateo Creek and San Margarita in the Camp Pendleton area, as well as San Luis Rey River.

Interestingly, some areas with zero or very few toad observations are predicted as high probability (e.g., Lower Otay River and less developed sections of Arroyo Trabuco). This disparity could be due to either lack of sampling effort in these areas, or other factors specific to these areas that may prevent toad reproduction. Further investigation would be necessary to reach a conclusion regarding the sources of this discrepancy.

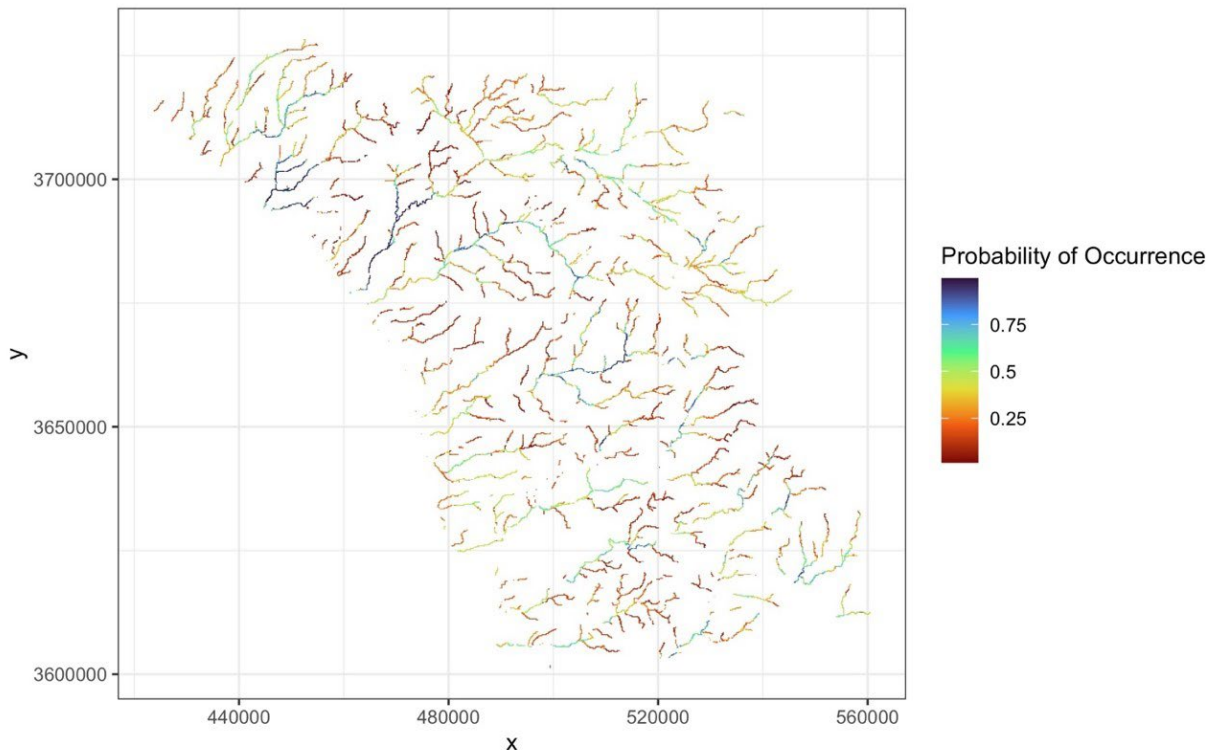


Figure ES4. Mean probability of occurrence of arroyo toad in RB9 region.

The arroyo toad probability of occurrence maps can be viewed at:

<https://sccwrp.sharepoint.com/:f:/s/SDHydroVulnerabilityAssessment/EolzSt7X0ihHtfU0wTBvpPgBf2OqiEPmB8fRQZ8CAsjUw?e=hd0qF1>.

Risk-decision framework

We developed a risk-decision framework to help evaluate potential effects of proposed projects under current conditions (Figure ES5) using the biologically relevant alteration data on CSCI, ASCI, and arroyo toad. The framework describes the steps that the Water Board staff can implement when reviewing project proposals that may affect hydrology. We also provide an accompanying csv table, shapefile, and KML file that contain relevant data for steps 1 through 5 of the decision framework.

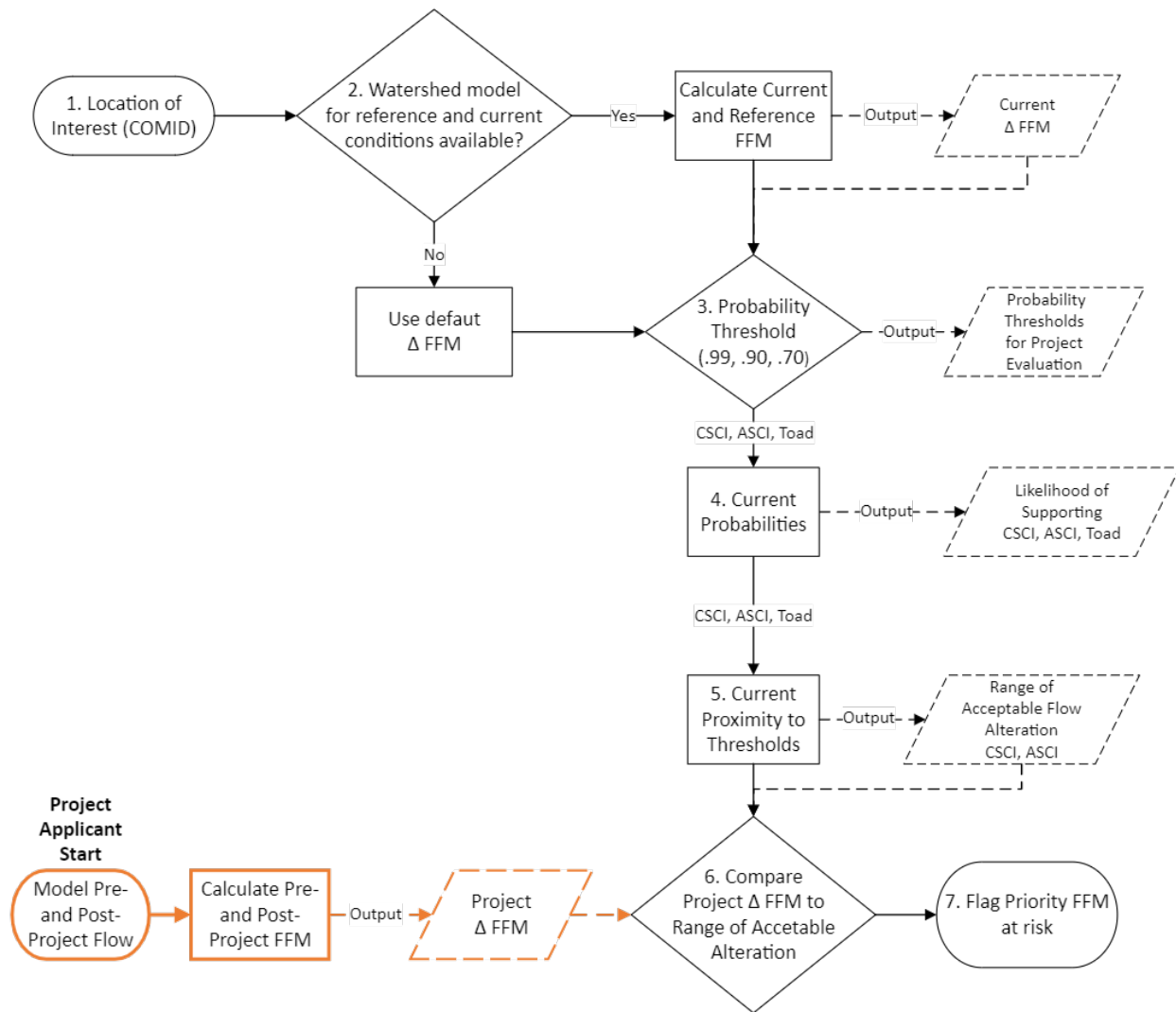


Figure ES5. Risk-decision framework for project review under current conditions.

For every modeled stream reach, we used the modeled change in FFM (delta FFM) to determine the probability of supporting CSCI, ASCI, and Arroyo Toad. Water Board staff have identified 3 risk (probability) thresholds: 0.99, 0.9, and 0.7. For every risk threshold, we determined the range of acceptable flow alteration for CSCI and ASCI. Figure ES6 shows a flow-ecology relationship for ASCI and dry-season baseflow magnitude and an example of a current proximity from the 0.7 probability threshold. In this example, the current delta FFM is depleted and lower than the risk threshold. If flows are depleted, we indicated how much proposed projects can increase flow to achieve the threshold. Staff can use this information to determine if proposed projects are at risk of altering functional flow metrics in a way that may pose a threat to ecology.

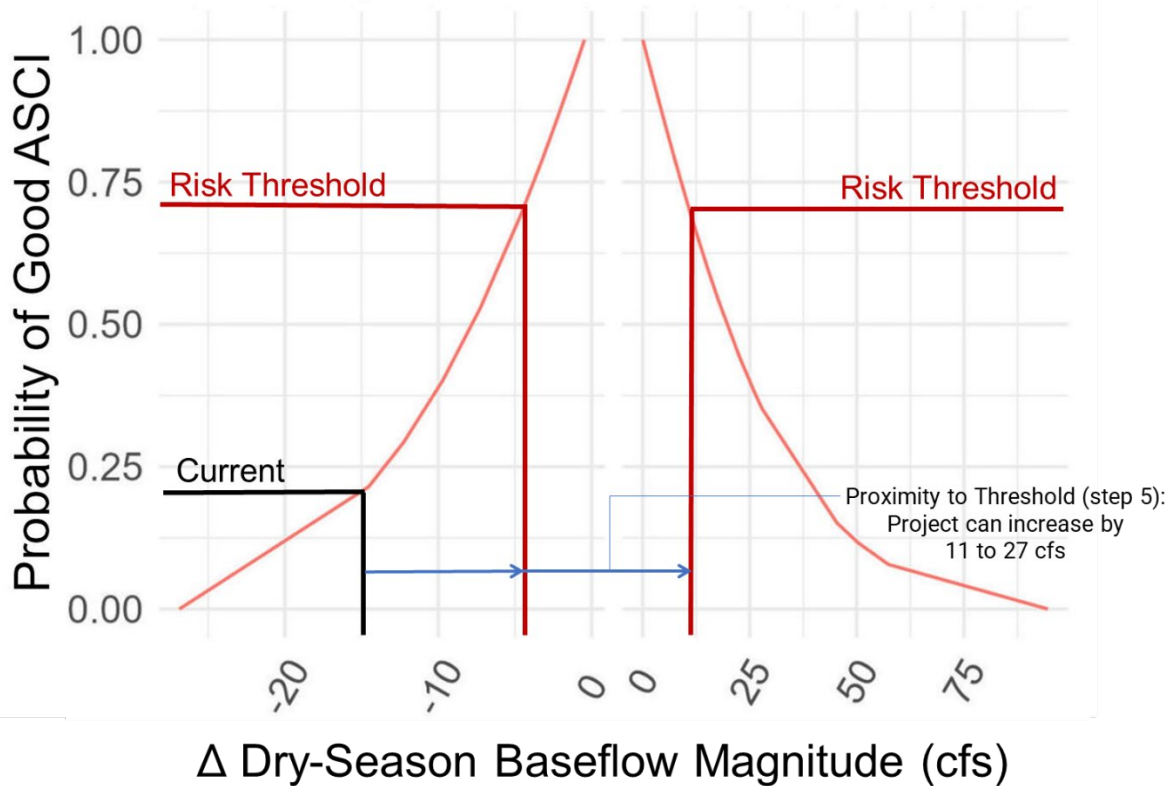


Figure ES6. Example of how current delta FFM from step 2 was used to determine the proximity to a threshold (0.7 probability (risk) threshold). For this example, the current dry-season baseflow magnitude is depleted compared to reference conditions. Projects would need to increase flow by 11 to 27 cfs to be within this threshold.

The data associated with the hydrologic risk-decision framework can be viewed at:

<https://sccwrp.sharepoint.com/:f:/s/SDHydroVulnerabilityAssessment/EnTKAUjiMypApbcw4RtMVtUBtSLiwtesSqF8r3l7V9lrw?e=G54TeU>.

A presentation to the Water Board staff on the decision framework can be viewed at:

<https://sccwrp.sharepoint.com/:f:/s/SDHydroVulnerabilityAssessment/EgmsCseAFoFLt4hLq8GaNj8BzT1FCQaEXpC8VpDOAY-F4g?e=PGl3aL>.

Next steps

This study developed hydrologic and ecological models that were used to evaluate hydrologic risk of current flow conditions on aquatic life. Next steps for a future phase of this study could include:

- Evaluation of low-flow measurement methods and refinement of the dry-season baseflow magnitude models, incorporating shallow groundwater contributions

- Integration of future climate scenarios and effects on functional flows and biology (CSCI, ASCI, and arroyo toad), including scenarios characterizing amplified swings of extremely dry years and wet years
- Refinements to the arroyo toad model, focusing on changes to populations over time
- Development of an interactive webtool for the decision framework, including integration of proposed project changes and other future scenarios

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PROJECT OVERVIEW

Hydrologic alteration is a pervasive issue across southern California and is a primary factor that contributes to the degradation of biological communities (Poff and Zimmerman 2010). The 2009-2013 regional bioassessment survey completed by the Stormwater Monitoring Coalition concluded that altered hydrology, largely as a result of stream channel modification, was the greatest risk factor associated with poor biological condition in southern California streams (Mazor 2015). Given its pervasiveness, there is a need to evaluate the extent and magnitude of hydrologic alteration over large regions to support planning, regulatory and management decisions. Moreover, we lack tools to readily evaluate risk of hydrologic alteration relative to future changes in climate, land use, and water use practices and to assess potential effects on stream ecological health. This project developed tools to help stakeholders and the Regional Board evaluate the potential severity of effects of proposed projects that have the potential to alter flows and to inform decisions regarding stream protection, restoration, and management in light of anticipated flow alteration.

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This report describes the methods, findings, and data products of the study to answer the three study objectives.

HYDROLOGIC ALTERATION – CSCI/ASCI

The following chapter describes the scope, methodology, and findings of objectives 1 and 2 of the project:

- 1) Evaluate the extent of current hydrologic alteration at the stream reach scale across the entire San Diego Regional Board jurisdiction (RB9 region)
- 2) Evaluate biologically relevant hydrologic degradation to streams in the RB9 region

Methods

Hydrologic Alteration Modeling

This study evaluated current hydrology across a suite of 24 functional flow metrics that describe the magnitude, timing, frequency, and duration of functional flow components identified as important for California streams (Yarnell et al. 2020). In California, functional flow components include the fall pulse flow, wet-season baseflow, peak flows, spring recession flow, and dry-season baseflow (Yarnell et al. 2020). The aim of our method was to estimate functional flow metric (FFM) change from reference to current conditions for river segments in the RB9 region, including ungauged segments, by using a machine learning (Random Forest, RF) algorithm. The algorithm establishes the relationship of climate and catchment descriptors, including descriptors of the physical environment and human impacts, to the change in functional flow metrics from the expected reference condition (Figure 1). This study leveraged previous research that estimated functional flow metrics under reference conditions (Grantham et al. 2022) and used that method as a framework to ensure compatibility between methods to estimate reference and impaired FFMs. The RF models were built using gage data from across California, to ensure sufficient training data, and applied the RF model to NHD stream segments in the Regional Board 9 (RB9) jurisdiction.

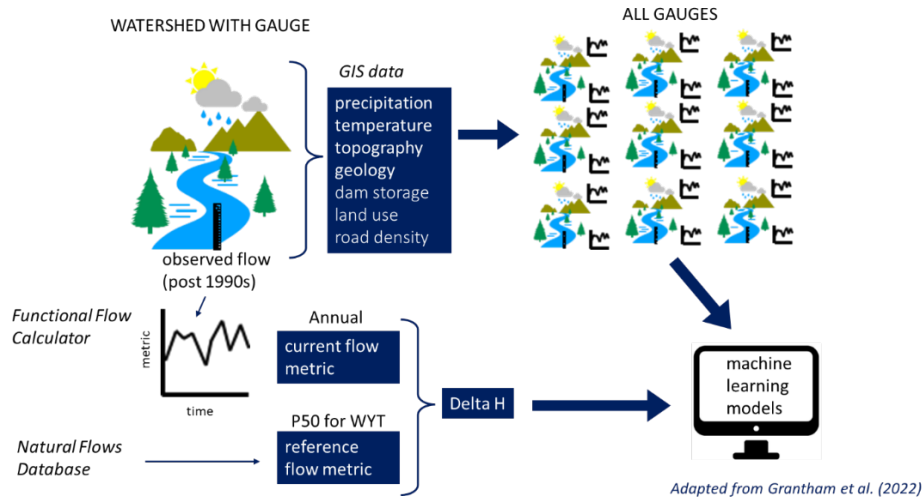


Figure 1. Overview of random forest modeling approach. Note that WYT means water year type (wet, moderate, or dry).

First, we utilized approximately 429 USGS gages in California, including reference and impaired gages (Falcone et al. 2010). Annual functional flow metrics were quantified for each gage 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>). The functional flows calculator has difficulty detecting the timing of seasonal flow transitions (i.e., transition from dry-season to wet-season or wet-season to spring recession) if the annual hydrograph lacks seasonality. In such cases, the timing, duration, and magnitude metrics cannot be estimated for the water year. Therefore, many NA values were produced, especially for aseasonal hydrographs. All NA values were omitted accordingly. Reference FFM for each water year type (dry, moderate, and wet) were predicted for all NHD reaches in California (Grantham et al. 2022). We refer to the difference between observed annual FFM values calculated from stream gages and reference FFM median values as delta FFM. As FFM reference percentiles exist for each water year type, delta FFM was calculated according to the water year type. We also calculated an additional peak flow metric, the 99th percentile of annual flow (Q99), at all gages as it was an important supplemental metric for CSCI (Irving et al. 2022). Given that we did not have reference predictions for Q99, we followed the methods of Grantham et al. (2022) and developed a reference Q99 random forest model using all reference gages and predicted annual reference Q99 at all stream reaches in the study region. We then used the annual reference Q99 prediction to calculate the delta value. We only included delta FFM values corresponding to the contemporary time period of water years 1990 to 2014, a time period that is representative of the 2006 land use predictor variables used in this study and years corresponding to readily available climatic variables from

Grantham et al. (2022). We did not use years prior to 1990 as land use variables were not available for this earlier timeframe. Therefore, both input data and model predictions corresponded to this contemporary time period.

We split the gage dataset into 70% of sites for model training and 30% of sites for independent model testing (testing sites) and excluded 10 outlier gages from training and testing (Figure 2). We identified and excluded 10 outlier gages with high delta FFM values that were in predominantly open space watersheds. These gages were typically located downstream of large-scale hydroelectric dams or dams that routinely release flows for water transfers or other operations. For example, outlier gages located downstream of Shasta Dam on the Sacramento River had observed flow augmentation of dry-season baseflow magnitude of around 6,000 cfs, in a catchment that is primarily undeveloped. Inclusion of these outlier gages may bias the models to predict high alteration in undeveloped catchments. The final models used all gages, excluding the outlier gages, to train the models.

For every gage, we obtained readily available, GIS-derived variables used in Grantham et al. (2022) corresponding to the physical characteristics of the contributing watershed upstream of the gage relating to topography, geology, soils, and hydraulic properties, as well as time-varying climatic variables derived from 800-m PRISM data (Daly et al. 2008). We also included eight watershed descriptors that relate to anthropogenic catchment impairments from StreamCat (Hill et al. 2016) including variables corresponding to agriculture, dams and water storage, roads, and population density. These impairment watershed descriptors correspond to the final set of predictor variables used in an impaired streamflow classification in California (Guitron 2020; Sandoval Solis and Lane 2021). The final list of input variables, descriptions, and data sources are provided in Appendix A.

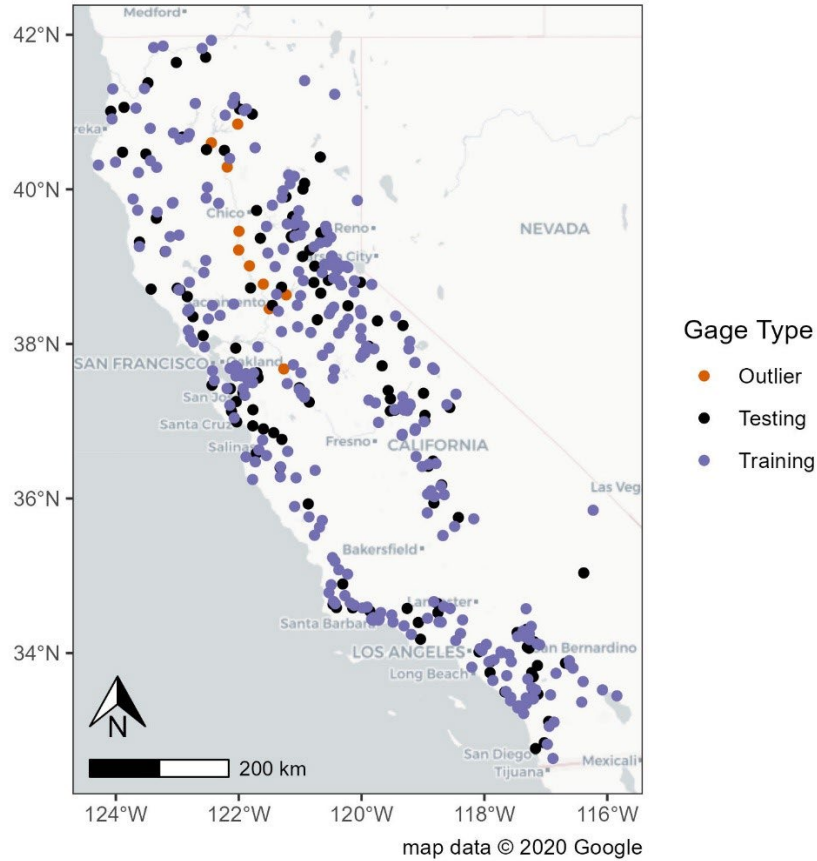


Figure 2. USGS gages used for model training, testing, and outlier gages that were excluded.

RF models were trained for each FFM by using reference and impairment catchment descriptors as predictor variables and delta FFM values as the dependent variable using “randomforest” and “caret” packages in R. We applied 10-fold cross-validation instead of gage-by-gage leave-one-out-cross-validation (LOOCV) due to model runtime. We used 1,001 trees to grow in each forest (ntree) to allow the model to have a “tie-breaker”, and mtry (number of variables randomly sampled as candidates at each split) was optimized by the caret package. We used R-squared as an objective function.

We evaluated model performance of the testing dataset based on methods by Grantham et al. (2022). We calculated performance metrics that characterize the dispersion and central tendency of model predictions compared to observed values. We constrained our performance evaluation to testing gages that had at least 10 or more years of observations. First, we calculated the percent of observed values that fell within the predicted interquartile range (IQR, range between 25th to 75th percentile values) and the inter-80th percentile range (I80R, range between 10th to 90th percentile values) for each site. For the percent in IQR and I80R, it is

expected that 50% and 80% of the observed data, respectively, should fall within these ranges. We also evaluated model performance by comparing the median prediction at each testing site to the median observed value. Several “goodness-of-fit” criteria typically used in hydrologic model performance (Moriassi et al. 2007; Eng et al. 2017) were calculated based on the median values including the observed to expected ratio (O/E), coefficient of determination (R²), percent bias (PBIAS), and Nash-Sutcliffe Efficiency (NSE). The mean value of each criterion across all sites was calculated. For peak flow magnitude metrics (i.e., 2-year, 5-year, and 10-year flood), we only calculated performance metrics of central tendency because only one value was calculated per site.

To evaluate model performance across all criteria, we standardized the criteria values between 0 (poor performance) and 1 (perfect performance) following Grantham et al. (2022). The mean percent in IQR was scaled by taking the absolute value from the difference between the calculated value and 50 divided by 50 and subtracted by 1. The same was done for the I80R, substituting 50 with 80. O/E was scaled for values greater than 1 by taking the inverse $\left(\frac{1}{O/E}\right)$. Percent bias was scaled by subtracting values from 100 and dividing by 100. NSE values greater than 0 were set to 0 and no changes were made to the R². A composite performance index was developed by averaging values of all six criteria, as well as a median composite performance index by averaging values of central tendency criteria only (R², percent bias, NSE, O/E). If the median composite index scored higher than the composite index using all criteria, this indicated that we have higher confidence in the median prediction rather than the entire distribution of delta FFM predictions at a given site. Qualitative ratings from Grantham et al. (2022), following guidance from Moriassi et al. (2007), were excellent (>0.9), very good (0.81–0.9), good (0.65–0.8), satisfactory (0.5–0.64), and poor (<0.5) model performance. Models with satisfactory or greater composite performance were deemed acceptable.

For FFM RF models with acceptable model performance, we predicted delta FFM values from WY 1990-2014. We retained the 50th percentile of predictions generated at all NHD reaches in the San Diego region. This value represents the expected median delta FFM at each stream reach. For all modeled FFM, we calculated relative alteration as the normalized difference between current and reference FFM values (delta FFM/reference FFM). We created categories of relative alteration based on the direction of alteration (augmentation + or depletion -) and alteration severity (very high, high, medium, or low). To define alteration severity, we evaluated the distribution of augmentation (all positive delta FFM values) for each metric and used the 25th, 50th, and 75th percentiles to define the alteration severity bins (Figure 3). The same process was done using the distribution of depletion (all negative delta FFM values) for all modeled FFM. All modeled stream reaches were classed into eight alteration categories by FFM

and mapped across the study region. We summarized the distribution of modeled reaches that have augmentation and depletion for every modeled FFM.

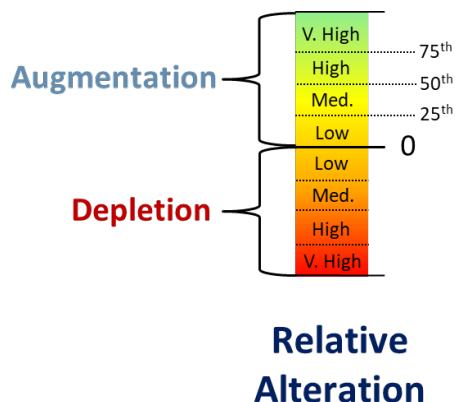


Figure 3. Relative alteration categories based on the distribution of augmentation and depletion for each modeled FFM.

Hydrologic Alteration Relative to Impacts to Benthic Communities

Biologically relevant flow alteration was assessed by identifying reaches where flow alteration is sufficient to be associated with a decline in biological condition as indicated by the standard statewide biological indices, the California Stream Condition Index (CSCI, Mazor et al. 2016) for benthic invertebrates and the Algal Stream Condition Index (ASCI, Theroux et al. 2020) for benthic algae. We analyzed reaches based on biotic alteration by relating biotic indices and FFM using flow ecology curves.

The flow ecology curves were applied following the approach in Irving et al. (2022). In brief, observed CSCI and ASCI bioassessment data from Southern California were modeled with the change in FFM from random forest hydrologic models described above. We used a total of 6 FFM in our flow ecology curve analysis. At each bioassessment site, the change in flow metrics from reference to current (hereafter referred to as delta FFM) were determined for each of the 6 FFM.

To ensure the most suitable flow ecology relationships, the 6 FFM were prioritized based on the following criteria:

- Can be modeled with confidence through the random forest approach, i.e., magnitude metrics
- Not highly correlated with other FFM

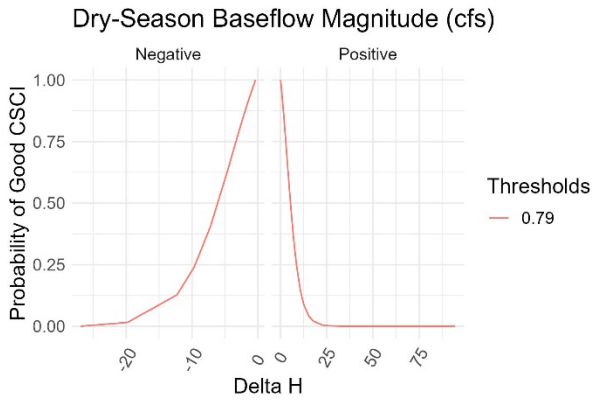
- Strong relationship through logistic regression analysis
- High data density for both depleted and augmented FFMs to ensure relationships are not driven by only a handful of points.

Delta FFM was applied in logistic regression to predict the probability of a healthy CSCI/ASCI score based on the currently accepted threshold values (CSCI = 0.79, ASCI = 0.86), providing relationships between the indices and each individual FFM. This resulted in flow ecology curves for each FFM. These logistic regression relationships were used to predict the probability of achieving a healthy ASCI and CSCI score for each NHD reach in the RB9 region using the delta FFM created in the random forest hydrological model.

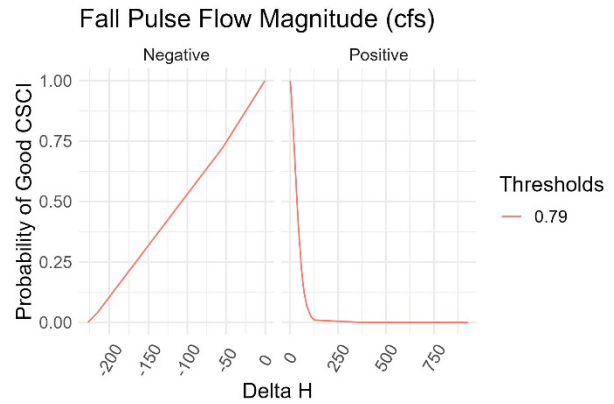
Flow targets relative to CSCI and ASCI

Delta FFM reflects values either lower or higher than those expected at a reference condition site. Using the flow ecology models (Figure 4 A-D), the delta FFM limits, (i.e., the upper and lower limits of the curves), were predicted based on three requested probabilities (0.70, 0.90, 0.99) of receiving a good quality CSCI or ASCI. The delta FFM limits describe the range of acceptable flow alteration to achieve at least the probability of the threshold of good ecological condition. These thresholds were used in the risk-decision framework, described in a subsequent section of this report.

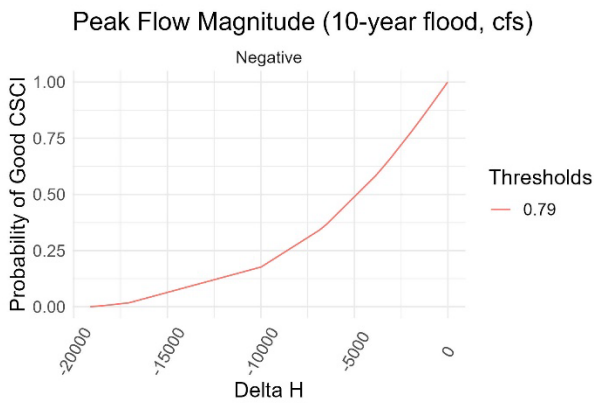
A. CSCI



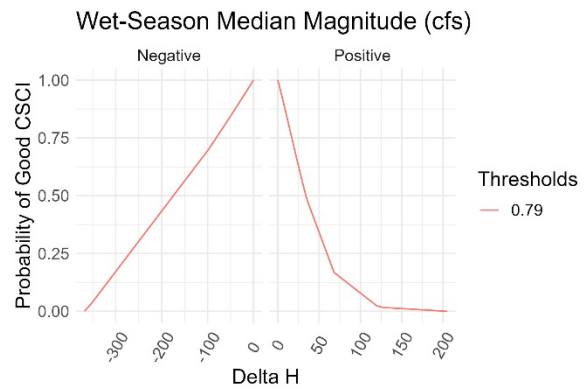
B. CSCI



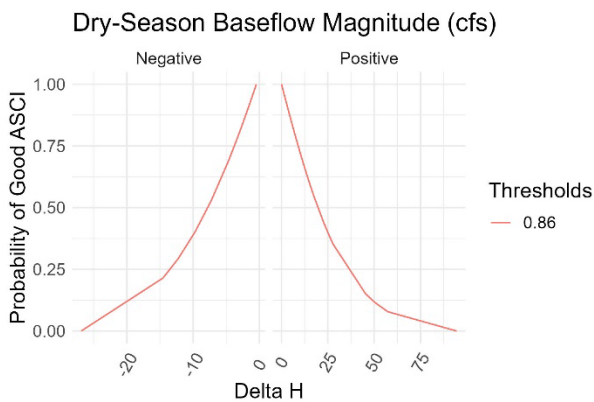
C. CSCI



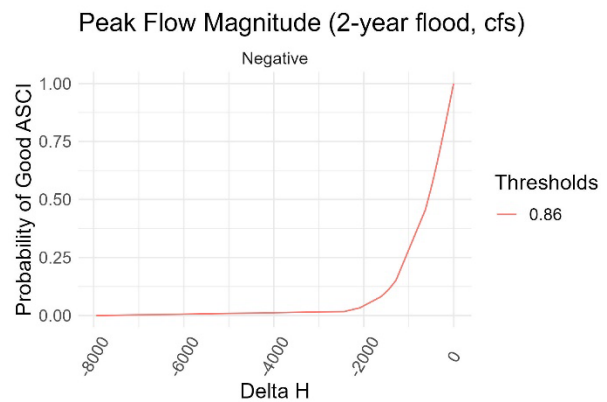
D. CSCI



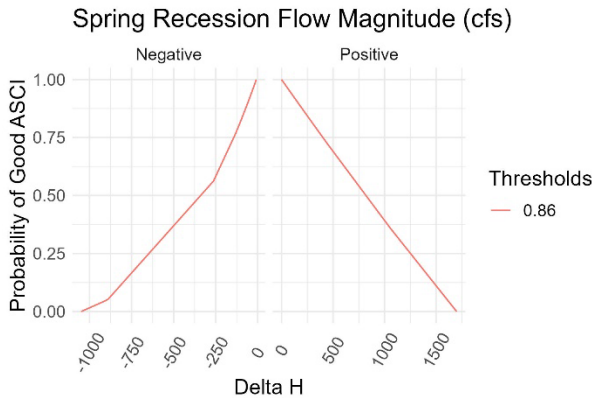
E. ASCI



F. ASCI



G. ASCI



H. ASCI

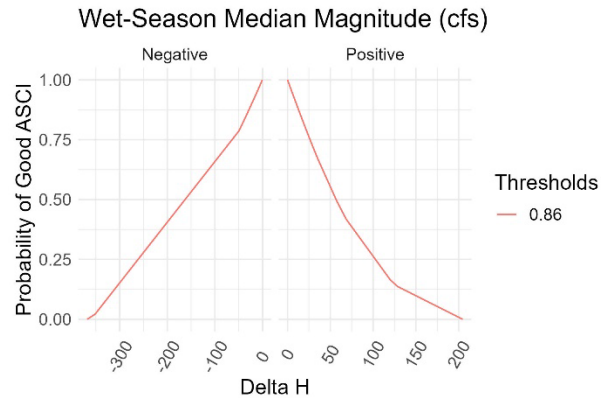


Figure 4. Flow ecology curves for the four respective FFMs chosen for each biological index: A) Dry-Season Baseflow Magnitude for CSCI; B) Fall Pulse Flow Magnitude for CSCI; C) Peak Flow Magnitude, 10-Year Flood for CSCI; D) Wet-Season Median Magnitude for CSCI; E.) Dry-Season Baseflow Magnitude for ASCI; F) Peak Flow Magnitude, 2-Year Flood for ASCI; G) Spring Recession Flow Magnitude for ASCI; and H) Wet-Season Median Magnitude for ASCI. Delta H represents the change in respective flow metric value from reference to current.

Key Findings

Hydrologic Alteration Modeling

A total of 124 gages that were excluded from model development were used to evaluate model performance across a suite of criteria (Table 1), with 7 gages located in the RB9 region. According to the composite performance index using all criteria, all peak flow magnitude models performed “good” (>0.65), the wet-season baseflow, fall pulse flow, and spring recession models performed “satisfactory”, and the dry-season baseflow models had “poor” model performance. According to the median composite performance index, all models performed satisfactory or above, except for the dry-season baseflow high magnitude model. This indicates that the model performed well in predicting the median alteration at each site for the time period of 1990 to 2014 but had lower performance in predicting the range of delta FFM at each site. For Q99, the reference and impaired (delta) model had “good” or “very good” model performance in terms of the median predictions (median composite index) and the range (composite index all). The Q99 delta model likely performed better than the other FFM because delta FFM was calculated at an annual basis using annual reference predictions, as opposed to using the median reference prediction by water year type. Calculating delta FFM using annual reference predictions will likely yield more realistic predictions of alteration at a given gage and improve annual delta FFM predictions. Although annual reference predictions are not readily available for the FFM at all reaches, a future study could develop the annual

reference predictions, recalculate delta FFM, and refine the random forest models built in this study.

Table 1. Functional flow metric model performance criteria.

Functional Flow Metric	Composite Index All	Composite Index Median
Fall Pulse Flow: Magnitude	Satisfactory (0.55)	Good (0.72)
Wet-Season Baseflow: Magnitude	Satisfactory (0.59)	Good (0.69)
Wet-Season: Median Magnitude	Satisfactory (0.59)	Good (0.67)
Peak Flow: Magnitude (2-year flood)	Good (0.7)	Good (0.7)
Peak Flow: Magnitude (5-year flood)	Good (0.76)	Good (0.76)
Peak Flow: Magnitude (10-year flood)	Good (0.79)	Good (0.79)
Peak Flow: Magnitude of largest storm (Q99) – Reference	Good (0.74)	Good (0.78)
Peak Flow: Magnitude of largest storm (Q99) – Delta	Good (0.65)	Very Good (0.81)
Spring Recession Flow: Magnitude	Satisfactory (0.56)	Satisfactory (0.63)
Dry-Season Baseflow: Magnitude	Poor (0.42)	Satisfactory (0.53)
Dry-Season Baseflow: High Magnitude	Poor (0.36)	Poor (0.42)

Relative alteration was mapped across the study region. Dry-season baseflow magnitude tended to be augmented across the region with higher levels of augmentation in the more

urbanized areas (Figure 5). Of the modeled stream reaches, 90% of the reaches had at least some level of flow augmentation in the dry season (Table 2).

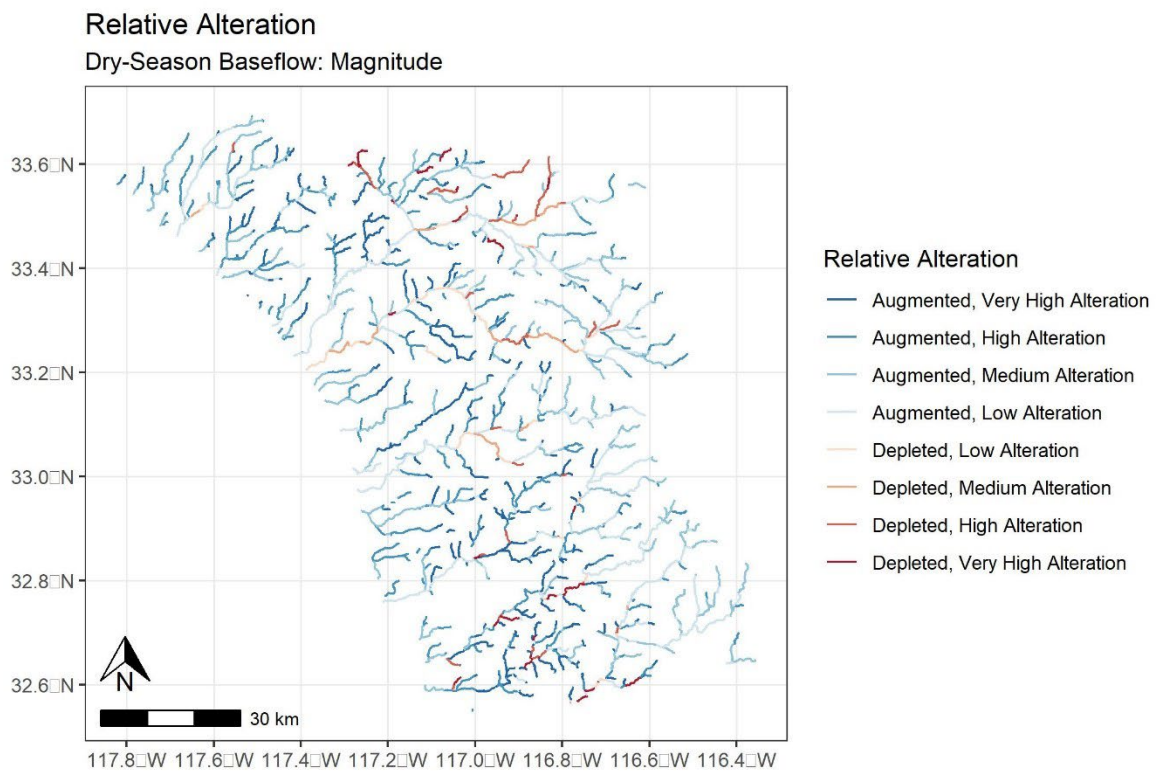


Figure 5. Relative alteration map for dry-season baseflow magnitude.

Table 2. Percentage and total number (n) of reaches in the study region that have augmentation and depletion for each functional flow metric.

Functional Flow Metric	Reaches Augmented (%)	Reaches Depleted (%)	Reaches Augmented (n)	Reaches Depleted (n)
Fall Pulse Flow: Magnitude	87	13	1831	285
Wet-Season Baseflow: Magnitude	76	24	1603	513
Wet-Season: Median Magnitude	83	17	1757	359
Peak Flow: Magnitude (2-year flood)	22	78	461	1655
Peak Flow: Magnitude (5-year flood)	49	51	1042	1074
Peak Flow: Magnitude (10-year flood)	52	48	1109	1007
Peak Flow: Magnitude of largest storm (Q99)	26	74	548	1568
Spring Recession Flow: Magnitude	94	6	1990	126
Dry-Season Baseflow: Magnitude	90	10	1912	204

Hydrologic Model Limitations

The hydrologic models developed in this study work well for broadly predicting relative alteration across the RB9 study region and evaluating the probability that hydrologic alteration may affect aquatic life uses under contemporary conditions. Caveats and limitations of the hydrologic modeling are summarized in the list below. Additional model refinements in a future phase of the study will increase overall confidence in model predictions.

1. **Model output is median Delta FFM from 1990 to 2014:** Hydrologic models performed at an acceptable level in predicting the median delta FFM at a site but had lower

performance predicting the range or distribution of delta FFM values from 1990 to 2014. These models are highly suited to investigate broad spatial patterns across the study region. However, as is, these models should not be used to evaluate annual delta FFM values and are therefore limited in evaluating temporal patterns of flow alteration at a given site. If annual reference expectations become available for all gages, the model will likely improve in making annual predictions, as illustrated with the Q99 model.

2. **Statistical models, local processes not explicitly modeled:** The random forest modeling approach relies on predictor variables that are available at all study reaches across the region. This approach does not explicitly capture local processes such as shallow groundwater inputs, diversions, and irrigation overspray, as data on these processes across the region were not available. Additional predictor variables that can broadly represent such processes should be included, as data become available. If not, mechanistic watershed models could be developed to better incorporate these processes.
3. **Resolution is at the NHD reach scale:** Model resolution is at the NHD reach scale, which matches the resolution of the predictor dataset. Additionally, smaller upper tributaries with watersheds less than $\sim 1 \text{ km}^2$ were excluded from model prediction as they were smaller than the minimum gage drainage area to prevent overextrapolation of the training gage dataset. Additional gages that are located in smaller tributaries could be added to the training dataset to provide higher model resolution. Alternatively, a hybrid model approach that uses both a mechanistic and statistical models could be used to provide predictions at smaller upper tributaries.
4. **Low flow models had lower performance:** Low flows typically have higher uncertainty in terms of direct measurements and modeling. Therefore, predicting alteration of low flows can be even more challenging, as flows may already be close to zero for the entire summer and alteration of low flows may be higher than the expected measurement uncertainty. Groundwater may also be important for accurately modeling low flows in certain systems. A more detailed watershed model that incorporates groundwater-surface water interactions may be warranted in certain watersheds to more accurately model alteration of low-flows. Additional low flow metrics (e.g., number of zero flow days) may also be ecologically important but were not modeled in this study.

Hydrologic Alteration Relative to Impacts to Benthic Communities

Through the metric prioritization process, we determined four priority FFM per index based on acceptable model performance and strength of relationships with the biological indicators. The selected FFMs for CSCI were dry-season median baseflow, 10-year flood magnitude, fall pulse magnitude, and wet-season median magnitude. The selected FFMs for ASCI were 2-year flood magnitude, spring recession magnitude, wet-season median magnitude, and dry-season baseflow magnitude.

Predicted probabilities for the RB9 area are summarized in Table 3. CSCI was the more sensitive index of the two, with all FFMs having a larger number of reaches with < 0.7 probability of achieving a healthy CSCI score, compared to ASCI. Fall pulse magnitude was the most sensitive FFM for ASCI, with 476 (22.05%) reaches with a <0.7 probability of a healthy score (Figure 6B). The least sensitive CSCI FFM was 10-year flood magnitude with 126 (5.95%) of reaches with a <0.7 probability of a healthy score (Table 3a). Note that there was not enough data to develop the flow-ecology relationship for positive peak metrics (i.e., bioassessment sites that had larger peak magnitudes compared to reference expectations). Therefore, reaches with augmented peak magnitudes were classed as “indeterminate”. This was the case for CSCI 10-year flood magnitude (Figure 6C) and ASCI 2-year flood magnitude (Figure 6F). For CSCI 10-year flood magnitude, 1,109 (52.41%) reaches were indeterminate while 461 (21.79%) were indeterminate for ASCI 2-year flood magnitude (which was also the most sensitive metrics for ASCI with 326 (15.41%) reaches with a <0.7 probability. The metrics with the highest number of reaches with a probability ≥ 0.7 of a healthy score for CSCI and ASCI were: wet season median magnitude with 1,846 (87.24%) reaches and spring recession magnitude with 2,074 (98.02%) reaches, respectively.

Table 3a. Probability of NHD reaches achieving a healthy CSCI score based on chosen flow metric.

Flow Metric	Reaches with ≥ 0.7 Probability	Reaches with < 0.7 Probability	Indeterminate Reaches
Dry-season baseflow magnitude	1,755 (82.94%)	361 (17.06%)	NA
10-year flood magnitude	881 (41.64%)	126 (5.95%)	1,109 (52.41%)
Fall pulse magnitude	1,640 (77.50%)	476 (22.50%)	NA
Wet-season median magnitude	1,846 (87.24%)	270 (12.76%)	NA

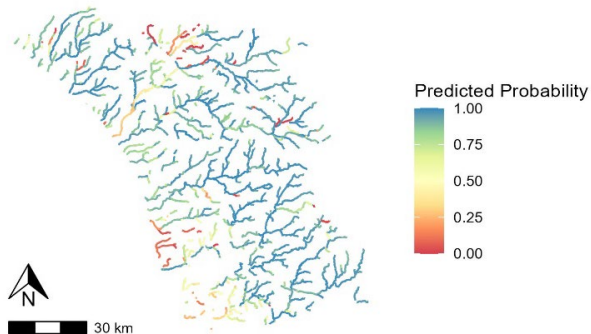
Table 4b. Probability of NHD reaches achieving a healthy ASCI score based on chosen flow metric.

Flow Metric	Reaches with ≥ 0.7 Probability	Reaches with < 0.7 Probability	Indeterminate Reaches
Dry-season baseflow magnitude	2,012 (95.09%)	104 (4.91 %)	NA
2-year flood magnitude	1,329 (62.81%)	326 (15.41%)	461 (21.79%)
Spring recession magnitude	2,074 (98.02%)	42 (1.98%)	NA
Wet-season median magnitude	1,918 (90.64%)	198 (9.36%)	NA

A

CSCI

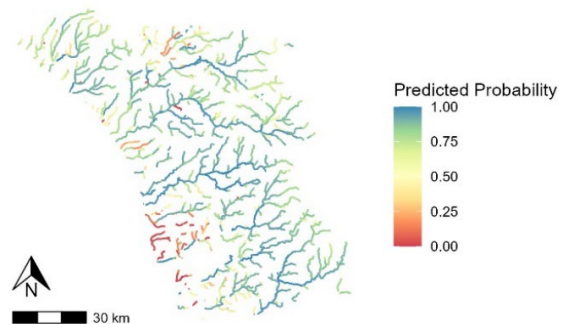
Predicted Current Probability
Dry-Season Baseflow Magnitude (cfs)



B

CSCI

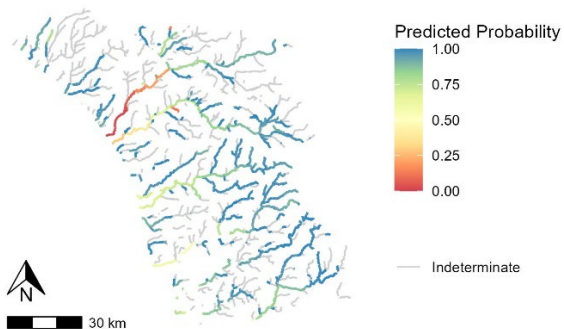
Predicted Current Probability
Fall Pulse Flow Magnitude (cfs)



C

CSCI

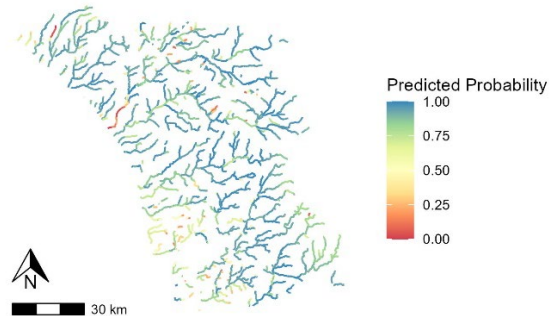
Predicted Current Probability
Peak Flow Magnitude (10-year flood, cfs)



D

CSCI

Predicted Current Probability
Wet-Season Median Magnitude (cfs)



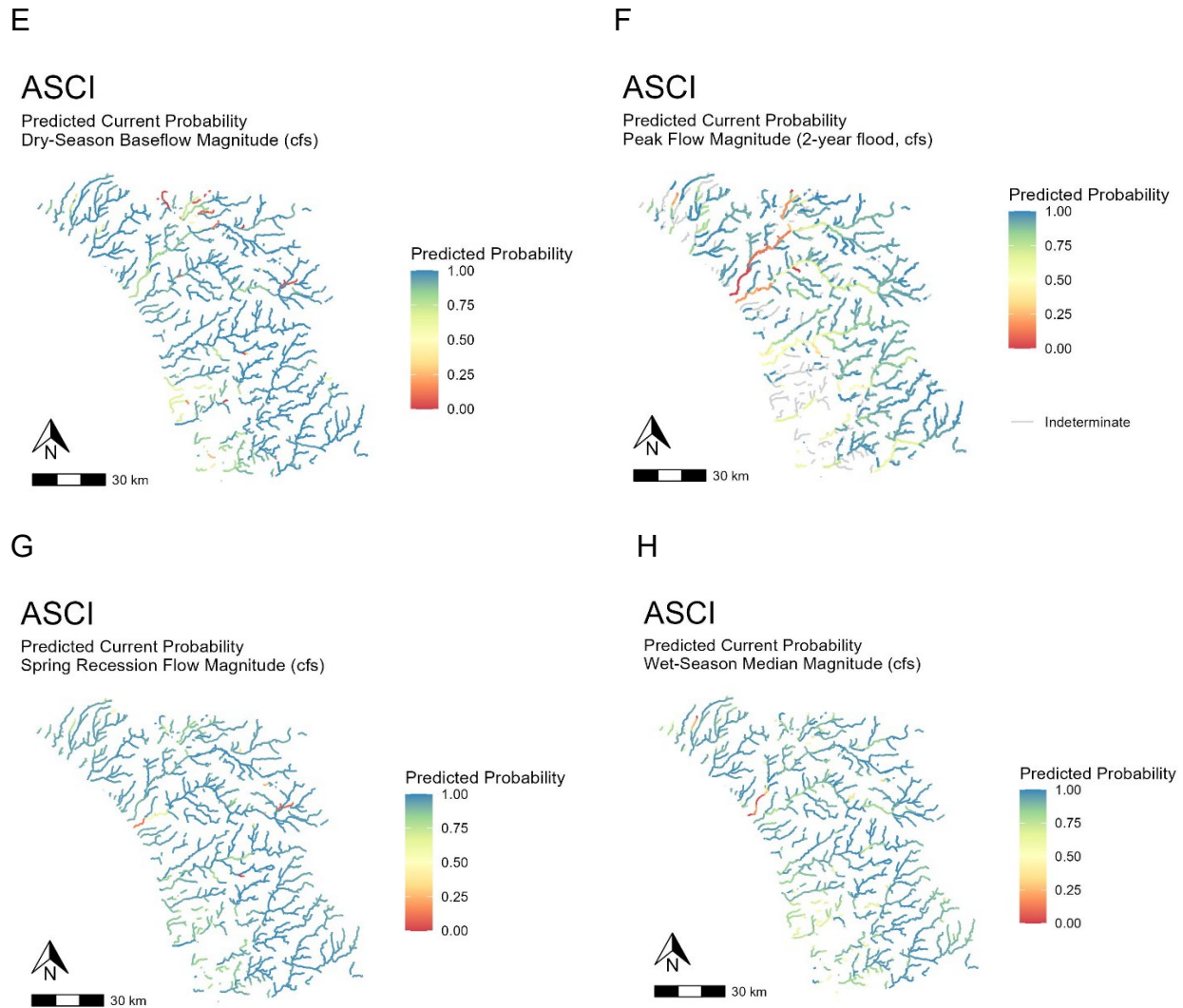


Figure 6. Predicted probability of achieving a healthy ASCI and CSCI score per chosen FFM metrics over the RB9 region.

Flow targets relative to CSCI and ASCI

Delta FFM limits were determined over three requested probability thresholds (0.7, 0.90, 0.99), for four selected metrics for CSCI and four selected metrics for ASCI (Table 5). The positive and negative limits represent how much augmentation (+) or depletion (-) of reference expectations can be tolerated in order to achieve at least the probability threshold. The limits can help flow managers understand the degree to which the current FFM is altered and can inform decision making regarding project proposals that may alter functional flows. For example, if a project proposal is expected to deplete flow below the delta FFM lower limit, this project may be flagged as there may be risk that the probability threshold may not be achievable.

Table 5a. Probability thresholds and regional delta FFM limits for CSCI dry-season baseflow magnitude. The delta FFM upper limit indicates the maximum amount flow metric can increase compared to reference expectations and the lower limit indicates the maximum amount the flow metric can decrease compared to reference.

Probability Threshold	CSCI Dry-Season Baseflow Magnitude: Upper Limit (cfs)	CSCI Dry-Season Baseflow Magnitude: Lower Limit (cfs)
0.70	3.35	-3.87
0.90	1.25	-1.64
0.99	0.17	-0.50

Table 6b. Probability thresholds and regional delta FFM limits for CSCI 10-year flood magnitude.

Probability Threshold	CSCI 10-Year Flood Magnitude: Upper Limit (cfs)	CSCI 10-Year Flood Magnitude: Lower Limit (cfs)
0.70	NA	-2703.45
0.90	NA	-880.99
0.99	NA	-105.27

Table 7c. Probability thresholds and regional delta FFM limits for CSCI fall pulse magnitude

Probability Threshold	CSCI Fall Pulse Magnitude: Upper Limit (cfs)	CSCI Fall Pulse Magnitude: Lower Limit (cfs)
0.70	23.05	-60.13
0.90	9.26	-20.06
0.99	1.88	-2.60

Table 8d. Probability thresholds and regional delta FFM limits for CSCI wet-season median magnitude.

Probability Threshold	CSCI Wet-Season Median Magnitude: Upper Limit (cfs)	CSCI Wet-Season Median Magnitude: Lower Limit (cfs)
0.70	20.24	-98.09
0.90	7.02	-31.99
0.99	0.75	-3.20

Table 9e. Probability thresholds and regional delta FFM limits for ASCI 2-year flood magnitude.

Probability Threshold	ASCI 2-Year Flood Magnitude: Upper Limit (cfs)	ASCI 2-Year Flood Magnitude: Lower Limit (cfs)
0.70	NA	-324.19
0.90	NA	-108.75
0.99	NA	-15.37

Table 10f. Probability thresholds and regional delta FFM limits for ASCI spring recession magnitude.

Probability Threshold	ASCI Spring Recession Magnitude: Upper Limit (cfs)	ASCI Spring Recession Magnitude: Lower Limit (cfs)
0.70	483.71	-174.19
0.90	159.18	-58.33
0.99	15.94	-12.79

Table 11g. Probability thresholds and regional delta FFM limits for ASCI wet-season median magnitude.

Probability Threshold	ASCI Wet-Season Median Magnitude: Upper Limit (cfs)	ASCI Wet-Season Median Magnitude: Lower Limit (cfs)
0.70	31.98	-83.71
0.90	10.33	-22.76
0.99	1.06	-2.53

Table 12h. Probability thresholds and regional delta FFM limits for ASCI dry-season baseflow magnitude.

Probability Threshold	ASCI Dry-Season Baseflow Magnitude: Upper Limit (cfs)	ASCI Dry-Season Baseflow Magnitude: Lower Limit (cfs)
0.70	10.98	-4.50
0.90	3.53	-1.73
0.99	0.39	-0.59

Deliverables Submitted:

For more information on the data deliverables submitted, please refer to the ReadMe file at:

https://sccwrp.sharepoint.com/:w:/s/SDHydroVulnerabilityAssessment/ET41kTqrbgZMIgnGwYonGicB6-af_zCJoJAtdHEp8dOJPA?e=TWJ3IX.

All data products can be downloaded at:

https://sccwrp.sharepoint.com/:f:/s/SDHydroVulnerabilityAssessment/Em6WdRTtc1dKqTspiyWve20B9kvAA3z_7xEbHARQs7cQwg?e=fVbve3.

ARROYO TOAD

The following chapter describes the scope, methodology, and findings of objective 2 of the project: Evaluate biologically relevant hydrologic degradation to streams in the RB9 region.

Methods

Selected Species of Management Concern

The arroyo toad (*Anaxyrus californicus*) was selected as our focal species of management concern for this study in accordance with our technical advisory group (TAG). The toad is native and endemic to Southern California and listed as endangered under the Endangered Species Act (Jennings and Hayes 1994; Sweet 1992; U.S. Fish and Wildlife Service (USFWS) 1994). The San Diego region supports some of the largest populations of toads south of Ventura County and is an important area for survival of the species. Adults are fully terrestrial, however; they are highly dependent on specialized flow-related habitat conditions for breeding and development. They require sandy pools with slow-moving, shallow flow in low-gradient streams, often utilizing stream terraces and sand bars (Cunningham 1964; Sweet 1992; Sweet and Sullivan 2005). These conditions are typically driven by natural flow regimes with scouring flood events (Jennings and Hayes 1994). Consequently, the toad is highly vulnerable to prolonged drought that may reduce the presence of suitable pools driven through the different characteristics of the seasonal flow regime, e.g., spring recession and summer baseflow to provide habitat, and winter peak flows for scouring events. Their vulnerability to drought makes the toad an ideal model species to assess vulnerability of streams in the RB9 region.

Model overview

We applied a Species Distribution Model to predict the probability of occurrence of arroyo toad to habitat-related variables describing flow, catchment, and landscape characteristics. The model is based on the previously developed landscape model from Treglia et al. (2015), with updated physical and biological data as well as the addition of flow metrics. Following the original model, our unit of analysis was 200 m x 200 m square grids stream network (as a gridded raster layer). The network was based on the National Hydrography Dataset (NHD, <https://www.usgs.gov/national-hydrography>). The predicted probabilities were reported per grid with associated NHD reach by COMID as well as a mean prediction per NHD reach.

Toad occurrence data

Toad occurrence data were collated from several sources (USGS, San Diego Regional Board, GBIF¹), which supplemented the data from the previously developed model. The data primarily consisted of presence only points, except for data sourced from USGS, which included a limited number of absence points. The data were collected through stream surveys mainly consisting of targeted day and nighttime visual encounters and dip net techniques. All life stages associated with toad breeding (egg, tadpole, juvenile & adult) require the same habitat conditions therefore were all included in the analysis. To be temporally consistent with the physical data, including the flow metric predictions from objective 1, only occurrence data observed between 1990 and 2014 was retained for analysis. In addition, all occurrence points outside 50 m of the stream were removed to reduce spatial error.

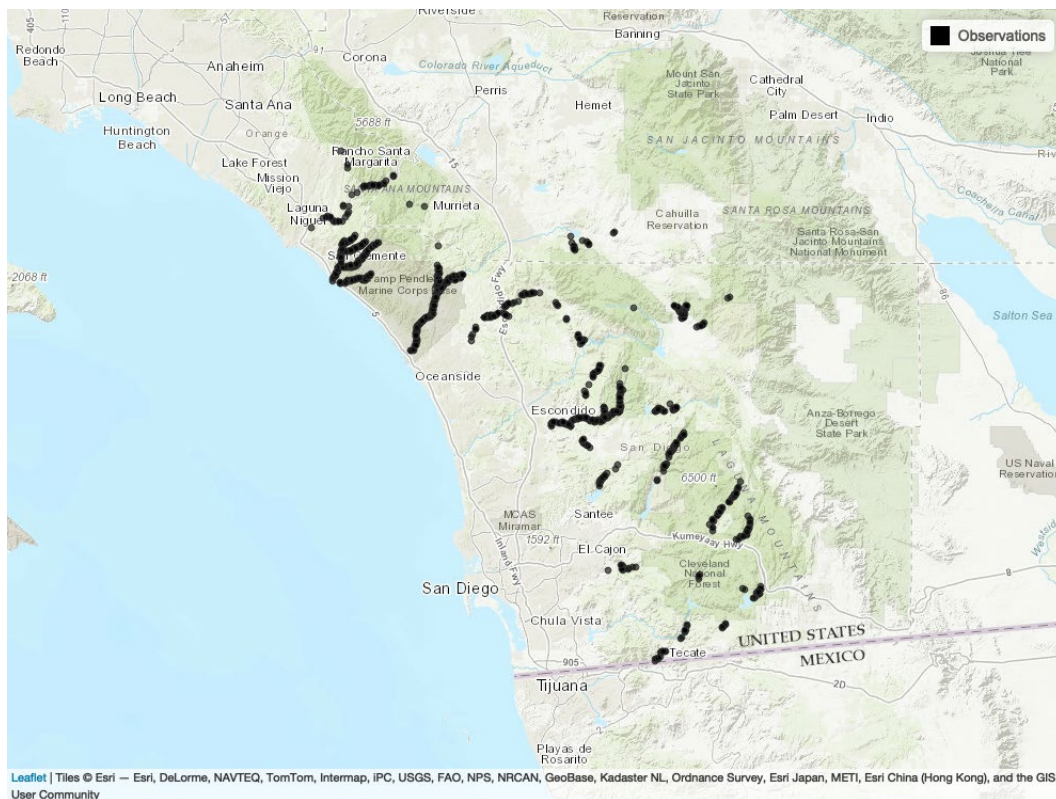


Figure 7. Map of arroyo toad observations in RB9 region between 1990 and 2014.

Physical data collection

The focus of this study was to assess the relationship between altered hydrologic regime and the distribution of arroyo toad. Nonetheless, several additional habitat characteristics are

¹ Available from: <https://www.gbif.org/>

critical in supporting toad habitat (e.g., sandy substrate with a low gradient). We therefore included landscape variables describing soil, topography, and geomorphology. All variables are described in Table 13 (adapted from Treglia et al. 2015, Table 1), and were updated to match the spatial extent of our current model. Importantly, the remote sensing data were extracted from multiple days due to cloud cover, combining calculations from September 5, 23 and 30, 2014 to represent dry season (low flows) and April 7, 14, and 16, 2014 to represent spring (high flows). All remaining landscape variables were sourced and calculated in the same manner as outlined in the original model. On occasion, some variable values could not be calculated for certain grid cells, these were removed from analysis. Note that climate variables were not included in our analysis explicitly. Considering climate is a large driver of hydrologic regime already used as inputs for the hydrologic predictions, and although we recognize that climate has a significant influence on toad distribution, including these variables would increase model complexity and create difficulties in interpreting the direct influence of hydrologic alteration on toad habitat.

Table 13a. Soil data applied in the random forest model, with names and abbreviations (if applicable), description, and source.

Name (Abbreviation)	Description	Value Used	Source
% Clay; % Sand; % Silt; Soil Water Storage Capacity	Weighted average of values per soil type across all soil layers, obtained from 1:250,000 scale soil data	Average, weighted by area of each soil type per analysis grid	Derived from STATSGO2 Soil Data, produced by the Natural Resources Conservation Service, U.S. Dept. of Agriculture ²

² Available from: <https://websoilsurvey.nrcs.usda.gov/app/>

Table 14b. Topography and geomorphology data applied in the random forest model, with names and abbreviations (if applicable), description, and source.

Name (Abbreviation)	Description	Value Used	Source
Elevation along Stream Segment	Estimated as lowest elevation	Calculated value per analysis grid	Calculated value per 10 m National Elevation Dataset (NED, Gesch 2007) ³
% Stream Slope	Estimated within each analysis grid using GIG data for elevation and streams	Value per analysis grid	Derived from 10m NED overlaid on 1:24,000 National Hydrologic Dataset ⁴
Multiresolution Index of Valley Bottom Flatness (MRVBF)	Measure of how flat and wide a valley is	Maximum value per analysis grid	Derived from 10 m NED using Flatness (MRVBF) valley is. Analysis grid methodology described by Gallant and Dowling (2003)
Vector Ruggedness Measure (VRM03 and VRM18)	Measure of how rugged terrain is, based on, analysis windows of 3 and 18 grids from 10 m NED	Minimum values per analysis grid	Derived from 10 m NED using methodology described by Sappington et al. (2007)
Catchment Area	Total area draining into a given analysis grid	Maximum value per analysis grid	Derived from sink-filled 10m NED using methodology described by Gruber and Peckham (2009)

³ Available from: <https://apps.nationalmap.gov/viewer/>

⁴ Available from: <https://www.usgs.gov/national-hydrography/national-hydrography-dataset>

Table 15c. Remotely sensed data applied in the random forest model, with names and abbreviations (if applicable), description, and source.

Name (Abbreviation)	Description	Value Used	Source
Brightness (Med,Var); Greenness (Med,Var); Wetness (Med,Var)	Indices of “brightness,” “greenness,” and “wetness” for April 7, 14, and 16 and September 5, 23, and 30, 2014	Median (Med) and Variance (Var) within analysis grid	Derived from Landsat TM imagery ⁵ using the Tasseled Cap Transformation (Crist and Cicone 1984) for Landsat data (NASA Landsat Program 2010)

Table 16d. Functional flow metrics applied in the random forest model, with names and abbreviations (if applicable), description, and source.

Name (Abbreviation)	Description	Value Used	Source
Dry season baseflow, Peak Flow (10, 5 & 2 Year Floods), Spring Recession, Fall Pulse, Largest Annual Storm (Q99), Winter Baseflow (Low & Median) Magnitude Metrics	Median magnitude of flow alteration (change or delta from reference expectations) from 1990-2014	Majority value per analysis grid	Derived from Task 11.1.i

The magnitude functional flow metrics (FFM) were included as our measure of hydrologic alteration. Although flow metrics associated with timing and duration may be important, we did not include them in this study as we could not model them with satisfactory performance in the hydrological model. Delta FFM (difference in FFM from reference to current conditions) were available from this study for 2116 NHD reaches in the RB9 region. To spatially match these metrics to the landscape variables in 200m gridded format, we converted the FFM values to a gridded raster layer. This resulted in repeated FFM values for every grid located in the same reach. Due to discrepancies in spatial resolution, several reaches could not be spatially matched

to all physical data inputs. Therefore, the model was built with 1865 NHD reaches (n cells = 16,021).

Species distribution modelling

We predicted the probability of toad occurrence by applying a classification Random Forest (RF) model. RF is a machine learning algorithm that uses a decision tree process that classifies sites into a probability of achieving a binary outcome (i.e., presence, absence) by relating toad observations to associated physical conditions in geographical space. The model was built with a total of 967 presence (occurrence) points and 977 absence points, which was a combination of both true absences and pseudo absence (background) points. The pseudo absence points were calculated through a spatially explicit method based on kernel density surfaces (Fitzpatrick et al. 2013; Phillips et al. 2009) of the 200 m gridded stream network. To avoid bias within the model, we aimed to include approximately the same number of pseudo absence points (combined with true absence points) as observation points (Barbet-Massin et al. 2012). The random forest model was built with only grids containing a presence or absence (n=1944) together with the corresponding physical data.

Multicollinearity

Although random forests can deal with correlating variables well, to avoid challenges with interpretation we assessed the physical data for multicollinearity, removing any variables with a Variance Inflation Factor (VIF) above 5 (James et al. 2021). The remaining variables were included in the model with the following criteria: 10,001 trees, 2 variables randomly sampled at each split, and a minimum node size of 5. The criteria were determined from pre-tuning the model and taking values that resulted in the highest model performance.

Validation and variable importance

A classification random forest includes an internal validation process, which calculates a misclassification rate (Out-Of-Bag error, OOB) by training the model on a subset of the data at each tree and testing the predictions on the remaining data. To supplement this process, we validated the model by randomly dividing the input data into training and testing datasets in an 80/20 split. Through 10-fold cross validation we derived four additional validation metrics describing how well the training data predicts the testing data: Receiver operator curve (ROC) a threshold-independent measure of model performance with values >0.8 considered as high performance (Thuiller et al. 2005; Swets 1988), sensitivity and specificity measures that describe how well the model predicts toad presence and absence, respectively, with values ranging between 0 – 1 and a value of 0.5 being no better than random, and the True Skills Statistic (TSS), a combination of sensitivity and specificity that ranges -1 to 1 with a value of

>0.6 considered as useful to excellent model performance. The OOB error rate from the internal validation process is expressed as a percentage, we converted the error rate to an accuracy rate by taking the difference from 100, therefore higher values indicate higher accuracy. Finally, to understand the individual influence of each physical variable, variable importance was extracted from the model and calculated as the mean decrease in accuracy if the variable were to be removed. We scaled the variable importance values and report as relative importance (%).

Model outcome

To ensure robust results and to minimize error, we ran the random forest ten times, which involved calculating a different set of pseudo absences and a different random data split for each model run. Each of the ten models were used to predict probability of occurrence separately across the RB9 region. The predicted probabilities, relative importance, validation, and accuracy measures were averaged across all models to achieve the final result. We present the predicted probability results as a probability map for the RB9 region, which we also provide as a csv, shapefile, raster file, and html interactive map (note that the html map needs to be downloaded locally to be viewed). Validation metrics are reported as mean \pm standard deviation.

Results

Overall, the random forest model performed well for all validation metrics (Table 17). These results indicate that the model has high predictive power according to the performance criteria set. In total, 6 variables were removed from the model due to multicollinearity, one of which was the FFM 5-year peak flow, which was highly correlated with the 10-year peak flow.

Table 17. Mean validation metric values of 10 models \pm standard deviation.

VALIDATION METRIC	VALUE
OOB (%)	84.6 ± 0.38
ROC	0.91 ± 0.02
SENSITIVITY	0.84 ± 0.04
SPECIVITY	0.83 ± 0.04
TSS	0.68 ± 0.01

The relative importance of each individual variables is illustrated in Figure 8. From the most important 10 variables, 6 described hydrological alteration (FFM), with 10-year peak flow being the most important overall. These results indicate that: 1) the model improves with the inclusion of FFM and 2) the flow alteration metrics are highly influential in the distribution of arroyo toad. Additionally, percent sand and clay were the most important landscape variables, underscoring the importance of predominant soil and substrate conditions on the distribution of arroyo toad. The mean probability of toad occurrence is shown in Figure 9. High probabilities are mostly evident in low gradient and more natural locations such as San Mateo Creek and San Margarita in the Camp Pendleton area, as well as San Luis Rey River. These areas correspond to the toad observations in Figure 7. Interestingly, some areas with zero or very few observations are predicted as high probability e.g., Lower Otay River and less developed sections of Arroyo Trabuco. This disparity could be due to either lack of sampling effort in these areas, or other factors specific to these areas prevent toad reproduction. Further investigation would be necessary to reach a conclusion regarding the sources of this discrepancy.

These results are provided as a shapefile (Arroyo_Toad_Prob_Occurrence_RB9.shp), raster file (Arroyo_Toad_Prob_Occurrence_RB9.tif), and a html interactive map (Arroyo_Toad_Prob_Occurrence_RB9.html).

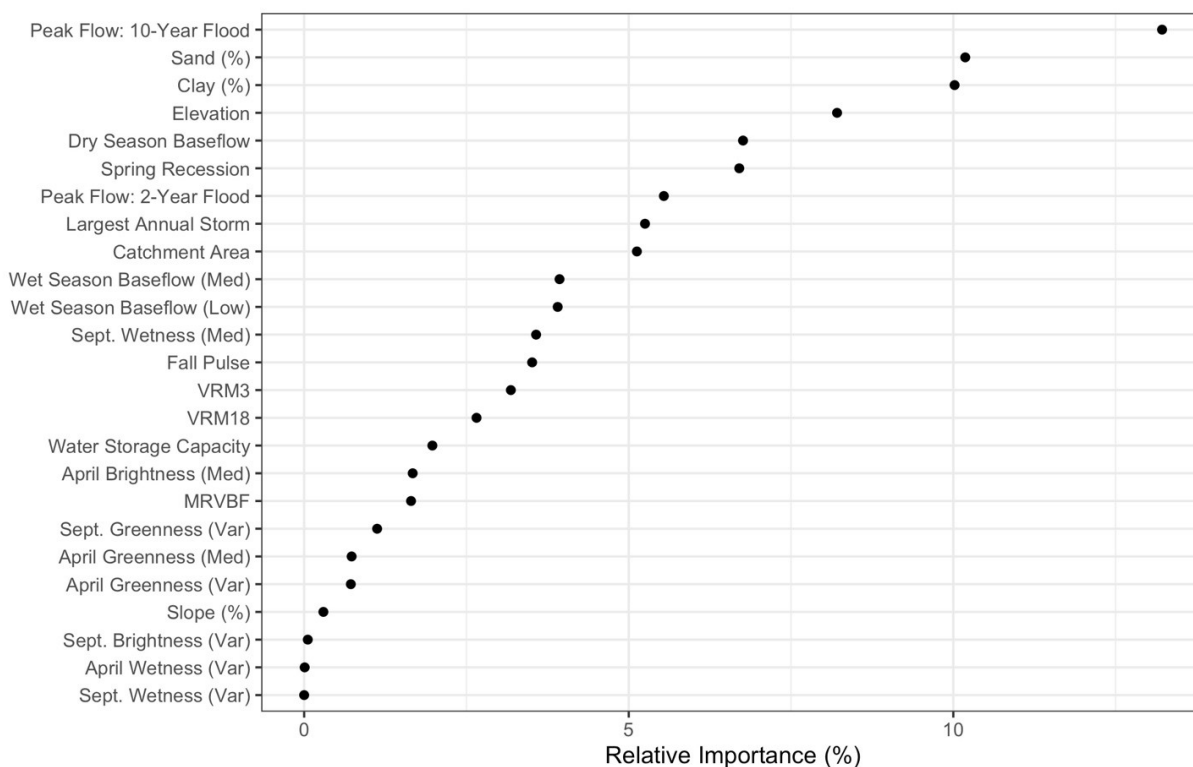


Figure 8. Mean relative importance of each individual metric.

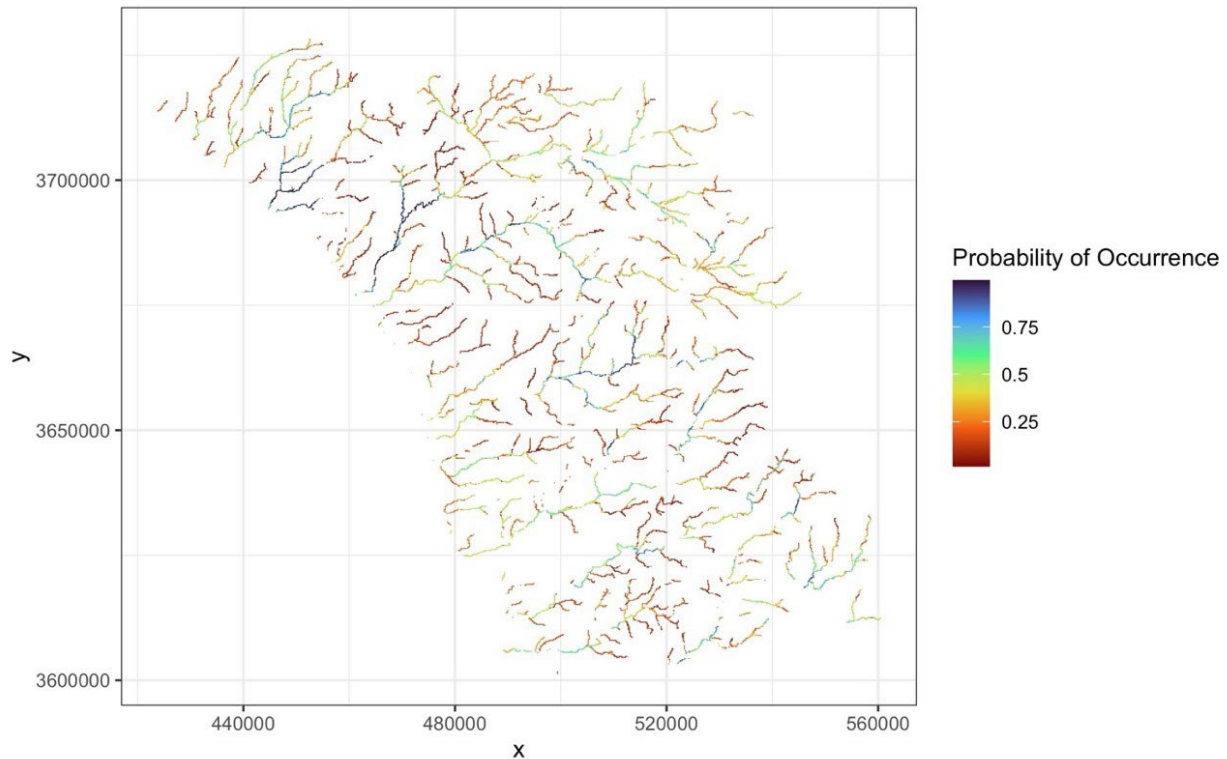


Figure 9. Mean probability of occurrence of arroyo toad in RB9 region.

Future considerations and improvements

Through working closely with arroyo toad experts from our TAG, several items were discussed that could improve the accuracy of the model.

- 1) **Hydraulic analysis of pools:** Predictor variables that describe the presence of suitable pools would likely improve the model by directly representing locations of suitable habitat. Although, the probability of occurrence predicted by the current model, at least in part, pertains to potential pool locations as it relates to preferred habitat conditions. Nonetheless, the addition of pool locations in relation to hydraulic conditions would further improve the model.
- 2) **Temporal analysis of drought impact:** Arroyo toads are highly vulnerable to prolonged drought, particularly if the duration of drought exceeds their estimated life span of 7-8 years (Fisher et al. 2018). Therefore, understanding the frequency and duration of drought would be a critical component in the understanding of toad vulnerability to altered hydrologic regime. An evaluation of this type would be more suited to a Population Viability Analysis (PVA) in order to relate toad life history structure to temporally diverse drought or low flow conditions.

- 3) **Finer resolution hydrologic model:** Our model includes repeated FFM values per NHD reach that currently does not include smaller tributaries in the region. Although our model works well in this setting, a finer resolution model would further improve predictions by 1) increasing the spatial extent of the analysis to include additional locations where arroyo toads may be present (i.e., smaller tributaries), 2) provide information on differences in FFM within each reach, 3) reduce spatial discrepancies with the additional physical data inputs, further increasing the spatial extent of the model.
- 4) **Improved low flow models:** Appropriate low flow conditions support toad habitat throughout the dry season and are critical for toad reproduction and development. Our model estimated dry-season baseflow magnitude as the 5th most important metric overall, and 2nd most important flow alteration metric, however the hydrological model from this study contains some uncertainty particularly with low flow metrics. Additional low flow metrics (e.g., number of zero flow days) may also be important to consider. Improving low flow observations together with a more comprehensive hydrological model would improve low flow estimates and describe timing and duration of low flows. In turn, this would further improve the accuracy of toad probability of occurrence were they to be included within the current model setting. Applying a more sophisticated hydrologic model would also improve timing, duration and/or frequency metric estimates for other components of the seasonal hydrograph found to be important for the toad (e.g., peak flows & spring recession).

Deliverables Submitted:

For more information on the data deliverables, please refer to the ReadMe file at:

<https://sccwrp.sharepoint.com/:w:/s/SDHydroVulnerabilityAssessment/EXsfA4uulgtHp6Gt2TAZdnMB3ahkSISUt-F9xDNfzpibXg?e=KU0rYp>

All data products can be downloaded at:

<https://sccwrp.sharepoint.com/:f:/s/SDHydroVulnerabilityAssessment/EolzSt7X0ihHtfU0wTBvpPgBf2OqiEPmB8fRQZ8CASojUw?e=hd0qF1>

RISK-DECISION FRAMEWORK

The following chapter describes the decision framework corresponding to objective 3 of the project: Develop a risk-decision framework and tool to evaluate proposed projects or alternative future scenarios in terms of their likelihood to alter hydrology to a level that may impair aquatic life uses.

Overview

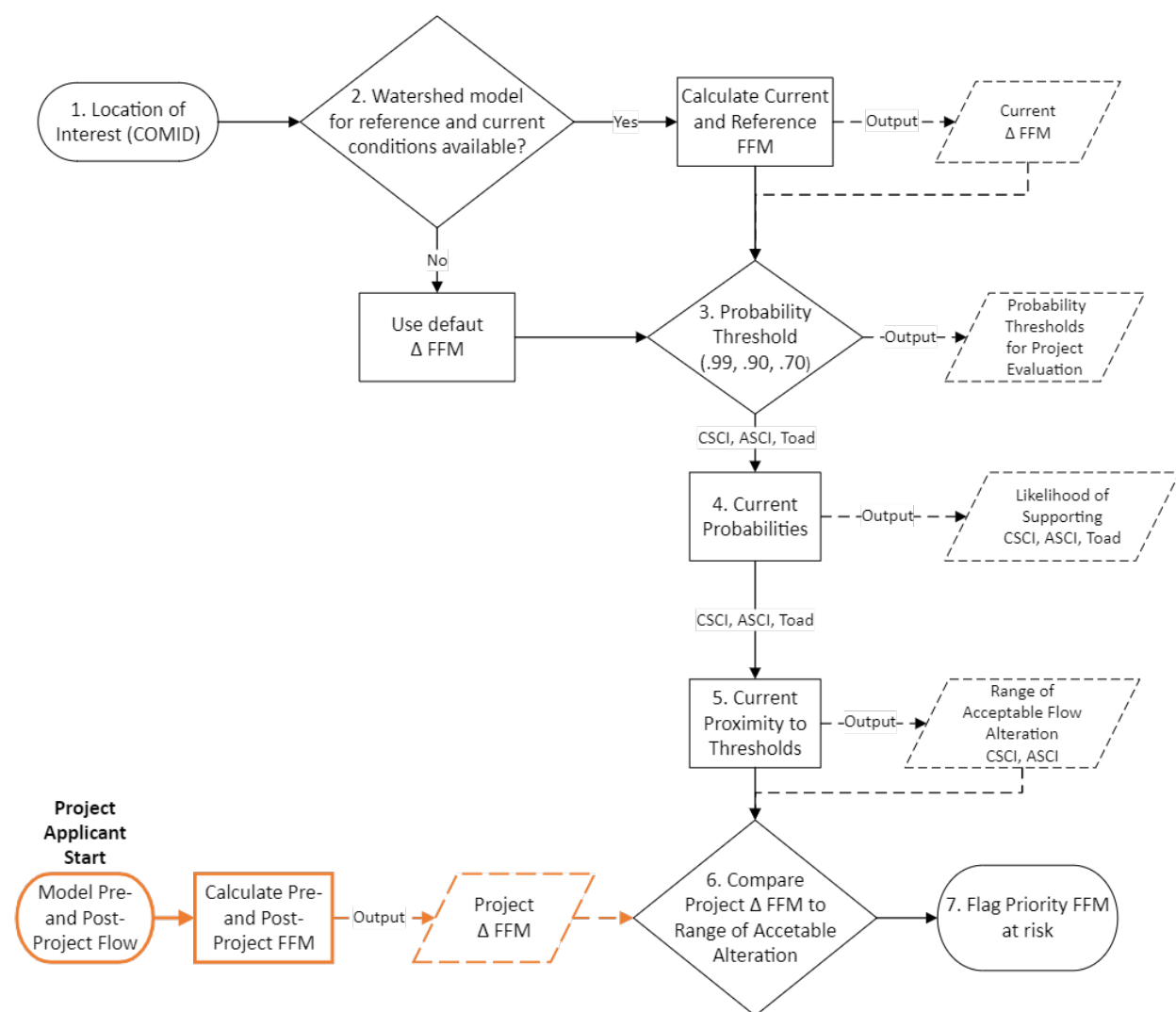


Figure 10. Risk-decision framework for project review under current conditions.

A risk-decision framework for project evaluation under current conditions was developed (Figure 10). Below describes the overall steps that the Water Board staff can implement when reviewing project proposals. Each step corresponds to the numbered boxes in the decision

framework. We also provided an accompanying csv table, shapefile, and KML file that contain relevant data for each step. Even without additional information, we provided data for steps 1 through 5 in csv, kml, and shapefile format.

1. Location of interest: Determine location of interest (LOI), a stream reach COMID that may be affected by the proposed project (e.g., downstream receiving stream reach from a project site). Water board staff should require project proponents to identify this reach COMID and Water Board staff can verify LOI using the final shapefile or kml file in Google Earth. COMIDs can also be found by using the geographic coordinate.
2. Watershed model: Determine if there is an existing watershed model that predicts both reference (unimpaired, pre-development) and current conditions at the LOI. This includes existing watershed models that were developed outside of this study where model confidence may be higher than the regional random forest model developed in this study. Alternatively, the project proponent may have modeled a reference condition scenario (optional) along with the current (pre-project) and future conditions (post-project or project alternatives, required). Current and reference flows from the watershed model should be used to calculate delta FFM (current change in flow metric value from reference expectation). Delta FFM represent current hydrologic alteration and are used to evaluate the likelihood of supporting beneficial uses (step 4). For south Orange County watersheds, a detailed watershed model was developed through the Flow Ecology Study to simulate current and reference hydrologic conditions. In this region, we have already calculated delta FFM and provide a csv, shapefile, and kml with data associated with steps 1-5.
 - a. If yes (i.e., a watershed model is available), calculate the current and reference FFM values using the functional flow calculator (detailed instructions are provided in Appendix B). Next, calculate the delta FFM as current FFM minus reference FFM. Note that for peak magnitude metrics (2-year, 5-year, and 10-year peak metrics), flow timeseries should be at least 15 years of continuous data. Calculate the median delta FFM values across all years for each metric. We only use the priority FFM for CSCI, ASCI, and Arroyo Toad for project review, based on the strength of relationships between flow alteration and biological response (Table 18).
 - b. If no (i.e., no watershed model is available), use the default delta FFM that were predicted at the LOI from this study using the regional random forest model. No additional calculations need to be done for this step (all the way to step 5). In the corresponding shapefile, kml, and csv files, we provide the relative alteration, direction of alteration (depleted or augmented compared to reference

conditions) and intensity, for the modeled FFM to provide context for the Water Board staff.

The priority functional flow metrics that were modeled in this study for CSCI, ASCI, and arroyo toad are highlighted in addition to three other timing and duration metrics that we could not model with confidence in this study but are of importance for CSCI and ASCI (Irving et al. 2022; Table 18). The timing and duration metrics will only be used for evaluation if there is a location-specific watershed model available.

Table 18. Priority functional flow metrics for CSCI, ASCI, and arroyo toad, indicated by “x”. Current delta FFM for nine magnitude metrics were modeled regionally and will be used as default values in the decision framework. Timing and duration metrics were not modeled in this study but could be calculated using a site-specific watershed model.

Priority Functional Flow Metric	CSCI	ASCI	Arroyo Toad	Model
Fall Pulse Flow: Magnitude	x		x	Regional model
Wet-Season Baseflow: Magnitude			x	Regional model
Wet-Season: Median Magnitude	x	x	x	Regional model
Peak Flow: Magnitude (2-year flood)		x	x	Regional model
Peak Flow: Magnitude (5-year flood)			x	Regional model
Peak Flow: Magnitude (10-year flood)	x		x	Regional model
Peak Flow: Magnitude of largest storm (Q99)			x	Regional model
Spring Recession Flow: Magnitude		x	x	Regional model
Dry-Season Baseflow: Magnitude	x	x	x	Regional model

Priority Functional Flow Metric	CSCI	ASCI	Arroyo Toad	Model
Dry-Season: Duration	x	x		Site-specific only
Spring Recession Flow: Duration		x		Site-specific only
Spring Recession Flow: Timing	x			Site-specific only

3. Probability Threshold: Water Board staff will determine which probability (risk) threshold they will use to determine acceptable flow alteration (delta FFM limits) at the LOI. The Delta FFM limits describe the range of acceptable flow alteration, as deviation from reference, to achieve at least the probability of the threshold of good ecological condition for CSCI and ASCI. The probability (risk) threshold could be interpreted as the probability of achieving the bio-objectives. The three requested probability thresholds to choose from are 0.99, 0.90, and 0.7 of achieving a CSCI or ASCI value above the accepted threshold values (i.e., 0.79 for CSCI and 0.83 for ASCI). The delta FFM limit for a 0.70 probability threshold indicates the range of flow alteration to achieve at least a 70% probability of good ecological condition or achieving the bio-objective (Figure 11). We provide all regional delta FFM limits (acceptable flow alteration as deviation from reference) for every priority FFM and probability threshold for CSCI and ASCI (Table 19). We also include the delta FFM limits for duration and timing metrics that were not modeled in this study but are of importance to CSCI and ASCI (Irving et al. 2022). For arroyo toad, we provide general guidance for flow alteration, instead of delta FFM limits, in step 5 (Table 31).

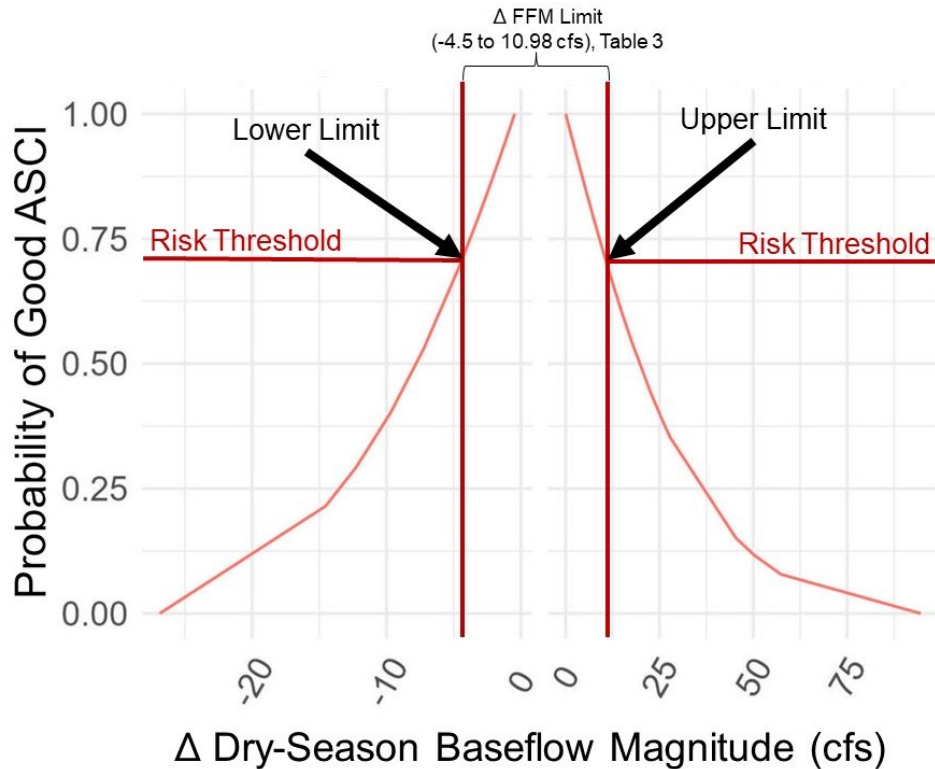


Figure 11. Example regional flow-ecology curve for ASCI and change in dry-season baseflow magnitude (from reference to current conditions). Regional curves are used to determine allowable flow alteration (delta FFM limit) for a given probability threshold, presented in Table 19 and Table 25. This example shows the 0.7 probability (risk) threshold. Where the risk threshold intersects the regional curves determine the lower and upper limit of alteration.

Table 19a. Probability thresholds and regional delta FFM limits for CSCI dry-season baseflow magnitude . The delta FFM upper limit indicates the maximum amount the flow metric can increase compared to reference expectations and the lower limit indicates the maximum amount the flow metric can decrease compared to reference. For example, for 0.7 probability for CSCI, dry-season baseflow magnitude can increase by no more than 3.35 cfs or decrease by no more than 3.87 cfs compared to reference conditions.

Probability Threshold	CSCI Dry-Season Baseflow Magnitude: Upper Limit (cfs)	CSCI Dry-Season Baseflow Magnitude: Lower Limit (cfs)
0.70	3.35	-3.87
0.90	1.25	-1.64
0.99	0.17	-0.50

Table 20b. Probability thresholds and regional delta FFM limits for CSCI dry-season duration.

Probability Threshold	Dry-season Duration: Upper Limit (days)	Dry-season Duration: Lower Limit (days)
0.70	21	-40
0.90	8	-14
0.99	1	-2

Table 21c. Probability thresholds and regional delta FFM limits for CSCI fall pulse magnitude.

Probability Threshold	CSCI Fall Pulse Magnitude: Upper Limit (cfs)	CSCI Fall Pulse Magnitude: Lower Limit (cfs)
0.70	23.05	-60.13
0.90	9.26	-20.06
0.99	1.88	-2.60

Table 22d. Probability thresholds and regional delta FFM limits for CSCI 10-year flood magnitude.

Probability Threshold	CSCI 10-Year Flood Magnitude: Upper Limit (cfs)	CSCI 10-Year Flood Magnitude: Lower Limit (cfs)
0.70	NA	-2703.45
0.90	NA	-880.99
0.99	NA	-105.27

Table 23e. Probability thresholds and regional delta FFM limits for CSCI spring recession timing.

Probability Threshold	Spring Recession Timing: Upper Limit (water year days)	Spring Recession Timing: Lower Limit (water year days)
0.70	9	-32
0.90	3	-11
0.99	0.3	-1.5

Table 24f. Probability thresholds and regional delta FFM limits for CSCI wet-season median magnitude.

Probability Threshold	CSCI Wet-Season Median Magnitude: Upper Limit (cfs)	CSCI Wet-Season Median Magnitude: Lower Limit (cfs)
0.70	20.24	-98.09
0.90	7.02	-31.99
0.99	0.75	-3.20

Table 25a. Probability thresholds and regional delta FFM limits for ASCI dry-season baseflow magnitude. The delta FFM upper limit indicates the maximum amount flow metric can increase compared to reference expectations and the lower limit indicates the maximum amount the flow metric can decrease compared to reference. For example, for 0.7 probability for ASCI, dry-season baseflow magnitude can increase by no more than 10.98 cfs or decrease by no more than 4.50 cfs compared to reference conditions.

Probability Threshold	ASCI Dry-Season Baseflow Magnitude: Upper Limit (cfs)	ASCI Dry-Season Baseflow Magnitude: Lower Limit (cfs)
0.70	10.98	-4.50
0.90	3.53	-1.73
0.99	0.39	-0.59

Table 26b. Probability thresholds and regional delta FFM limits for ASCI dry-season duration.

Probability Threshold	Dry-season Duration: Upper Limit (days)	Dry-season Duration: Lower Limit (days)
0.70	32	-53
0.90	11	-17
0.99	1	-2

Table 27c. Probability thresholds and regional delta FFM limits for ASCI 2-year flood magnitude.

Probability Threshold	ASCI 2-Year Flood Magnitude: Upper Limit (cfs)	ASCI 2-Year Flood Magnitude: Lower Limit (cfs)
0.70	NA	-324.19
0.90	NA	-108.75
0.99	NA	-15.37

Table 28d. Probability thresholds and regional delta FFM limits for ASCI spring recession magnitude.

Probability Threshold	ASCI Spring Recession Magnitude: Upper Limit (cfs)	ASCI Spring Recession Magnitude: Lower Limit (cfs)
0.70	483.71	-174.19
0.90	159.18	-58.33
0.99	15.94	-12.79

Table 29e. Probability thresholds and regional delta FFM limits for ASCI spring duration.

Probability Threshold	Spring Duration: Upper Limit (days)	Spring Duration: Lower Limit (days)
0.70	18	-24
0.90	6	-8
0.99	0.6	-1

Table 30f. Probability thresholds and regional delta FFM limits for ASCI wet-season median magnitude.

Probability Threshold	ASCI Wet-Season Median Magnitude: Upper Limit (cfs)	ASCI Wet-Season Median Magnitude: Lower Limit (cfs)
0.70	31.98	-83.71
0.90	10.33	-22.76
0.99	1.06	-2.53

4. Current probabilities: At all COMIDs, we have predicted the likelihood of supporting beneficial uses (as a probability), as represented by CSCI, ASCI, and arroyo toad, based on current hydrologic alteration (default delta FFM from step 2). For CSCI and ASCI, we provide probabilities for each individual flow metric and for arroyo toad, we have an overall probability that integrates multiple flow metrics. Predicted probabilities use the flow ecology models for CSCI, ASCI, and arroyo toad developed in this study. Staff should indicate whether the probability thresholds for all endpoints from step 3 are achieved or not based on the current probabilities.

- a. If using your own delta FFM from watershed model (answered “yes” to step 2), visually estimate current probability of supporting CSCI and ASCI using the modeled delta FFMs and the regional curves. Further instructions are provided in the illustrative example in Appendix C. For arroyo toad, regional curves were not available to estimate current probabilities using modeled flow metrics. At a future date, a web tool can be developed that would calculate the expected probability of supporting arroyo toad, CSCI, and ASCI under current conditions.
5. Current Proximity to Thresholds: The current proximity to a threshold based on the default current delta FFM (step 2) for CSCI and ASCI are provided. Figure 12 shows an example of a current proximity from the 0.7 probability threshold. In this example, the current delta FFM is depleted, or lower than the delta FFM limit. If flows are depleted, we indicate how much proposed projects can increase flow to achieve the threshold. Alternatively, if the current delta FFM is augmented, or higher than the delta FFM limit, we indicate how much proposed projects can decrease flow to achieve the threshold. If the current delta FFM is within the limit, we indicate how much proposed projects can increase or decrease flows to stay within the limit. For arroyo toad, we provide general guidance on the direction of alteration that tends to decrease probability for arroyo toad (Table 31). However, it is recommended that a webtool be developed so staff can evaluate if project flow changes increase or decrease probability for arroyo toad based on recalculation of the toad model output. Also note that substrate, and other factors need to be present in order to create suitable habitat for the toad.
 - a. If using your own delta FFM from watershed model (answered “yes” to step 2), the proximity to thresholds for CSCI and ASCI needs to be calculated with the revised delta FFM values. We provide the following steps to do so, but ideally this would automatically be done in a webtool. Also, see Appendix C for an example of this process.
 - i. Determine if the current delta FFM is within, above, or below each delta FFM limit for CSCI and ASCI from step 3, Tables 8 and 9.
 - ii. Calculate proximity to threshold: current delta FFM – upper limit and current delta FFM – lower limit for every priority metric and threshold
 - iii. Interpret proximity to threshold:
 1. If delta FFM is within the limit, then the values from the previous step will indicate how much proposed projects can increase or decrease flows to stay within the limit

2. If delta FFM is below the limit, then the values from the previous step will indicate how much proposed projects can increase flow to achieve the threshold
3. If delta FFM is above the limit, then the values from the previous step will indicate how much proposed projects can decrease flow to achieve the threshold

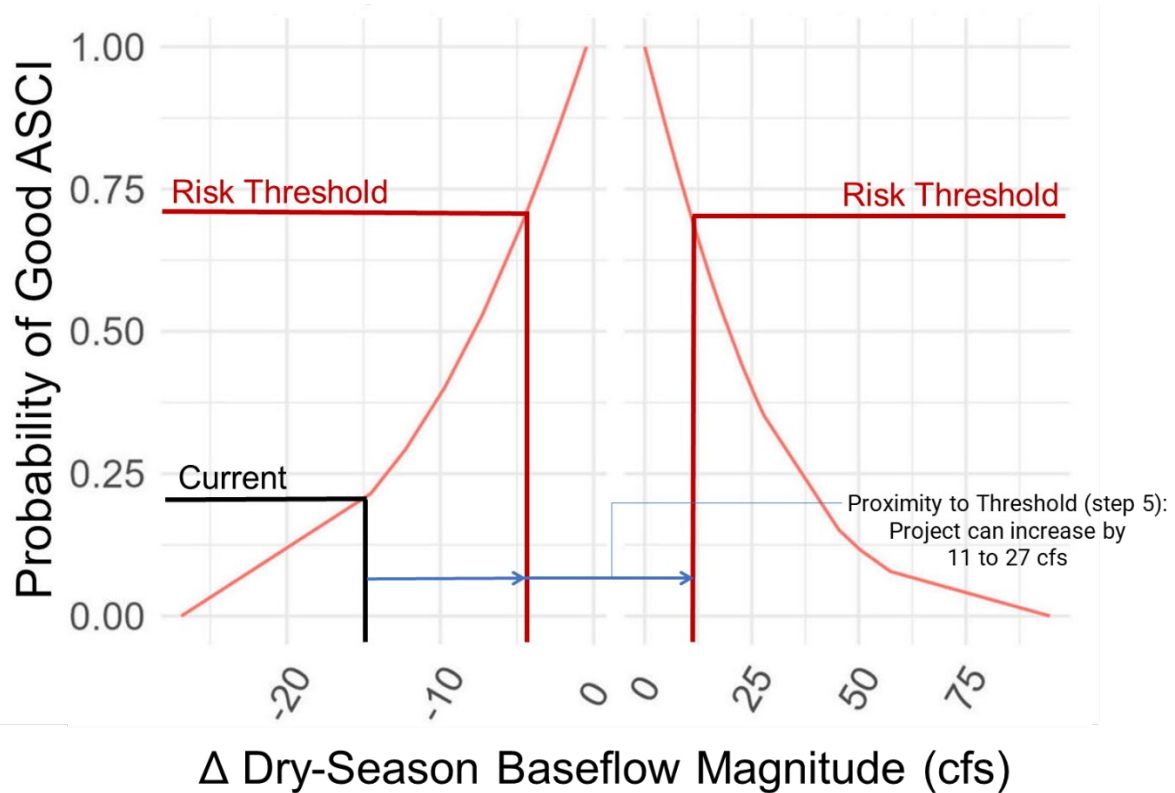


Figure 12. Example of how current delta FFM from step 2 is used to determine the proximity to a threshold (0.7 probability (risk) threshold). For this example, the current dry-season baseflow magnitude is depleted compared to reference conditions. Projects would need to increase flow by 11 to 27 cfs to be within this threshold.

Table 31. General guidance on flow alteration direction that tends to increase probability for arroyo toad sorted by relative importance of flow metrics. Peak flow (10-year flood), spring recession, and dry-season baseflow magnitudes are the most influential flow metrics for arroyo toad. Note that peak flow (5-year flood) was removed due to multicollinearity. Also note that substrate, and other factors need to be present in order to create suitable habitat for the toad.

Priority Functional Flow Metric	General Guidance for Arroyo Toad	Relative Importance (%)
Peak Flow: Magnitude (10-year flood)	Increase tends to increase probability	13
Spring Recession Flow: Magnitude	Increase tends to increase probability	7
Dry-Season Baseflow: Magnitude	Reduction tends to increase probability	7
Peak Flow: Magnitude (2-year flood)	Unable to determine	6
Peak Flow: Magnitude of largest storm (Q99)	Increase tends to increase probability	5
Wet-Season Baseflow: Magnitude	Reduction tends to increase probability	4
Wet-Season: Median Magnitude	Reduction tends to increase probability	4
Fall Pulse Flow: Magnitude	Reduction tends to increase probability	4

6. Compare Project Delta FFM to Range of Acceptable Alteration: Water Board staff will review the project delta FFM supplied by the project proponent. The project delta FFM represents the expected change in flow metric from current pre-project conditions and will be compared to the current proximity to thresholds (step 5). If multiple project alternatives are being contemplated, the expected change in flow (delta FFM) for each alternative should be reviewed.

7. Flag FFM at Risk: For all priority metrics, if the project delta FFM exceeds the allowable flow alteration for CSCI and ASCI determined in step 5, then that flow metric should be flagged. For arroyo toad, a webtool is needed to predict the post-project probability as the model integrates all magnitude flow metrics. Potential decision rules for CSCI and ASCI can be applied that can be used to synthesize results across the three biological endpoints, depending on water board input and need.

Summary of project proponent requirements

The project proponent requirements that will be used in the decision framework are:

- Determine receiving stream reach LOI using the kml or shapefile provided. Indicate COMID and provide a map of the proposed project, watershed, and LOI.
- Determine delta FFM (change in FFM from pre-project condition):
 - Ideally, project proponents should develop a calibrated watershed model that simulates daily streamflow (cfs) for current conditions (pre-project) and future conditions (post-project for all project alternatives being evaluated) for at least 15 continuous years. Assume that the climate (rainfall and temperature) stays the same in all scenarios modeled.
 - Optional: Project proponents can choose to model a reference condition scenario. If this option is chosen, the current alteration can be calculated and used for project evaluation in lieu of the regional hydrologic model prediction of current delta FFM from this study (“yes” for step 2). This option may be preferred by the project proponent because the current pre-project and post-project delta FFM may be more comparable since they were derived from the same watershed model that share inherent model uncertainties.
 - Alternatively, project proponents could use other established empirical relationships between rainfall, land cover, and runoff to estimate pre- and post-project discharge. For example, the rational method or SCS curve number method could be used to estimate flow. Although watershed models use these established relationships to calculate runoff, watershed models can better represent the spatial heterogeneity in slope, land cover, and soil within the entire watershed. Similarly, post-project conditions will likely be better characterized using a watershed model. That being said, using a simple equation

can provide a relatively simple and cost-effective method to estimating change in flows when time and budget are limiting.

- Calculate annual FFM values for all scenarios modeled (i.e., current pre-project and project alternatives being evaluated) for the entire modeled time period of at minimum 15 continuous years. See Appendix B for details on calculating FFM.
- Calculate the change in FFM values from current pre-project to future post-project conditions (project delta FFM) on an annual basis for all project alternatives and determine the median project delta FFM for every priority flow metric.
 - If reference condition was modeled, calculate the current delta FFM as current FFM minus reference FFM for every year. Indicate the median current delta FFM for every priority flow metric in Table 1.

Illustrative Examples

We provide two examples to illustrate the decision framework using actual COMIDs with hypothetical project proposals: 1) step 2 is “no”, do not have detailed watershed model of reference and current conditions, in which the default current delta FFM values are used, and 2) step 2 is “yes”, have a detailed watershed model of reference and current conditions (see Appendix C for example 2).

Example 1: Do not have detailed watershed model of reference and current conditions (step 2 is “no”)

1. Location of interest: The hypothetical project discharges into a stream reach on Santa Maria Creek and has the potential to affect COMID 20329864.
2. Watershed model: There was no existing watershed model of reference and current conditions readily available. The default current delta FFM values were used for this COMID. The relative alteration based on the default delta FFM showed overall streamflow depletion compared to reference conditions for all magnitude metrics and low to medium alteration severity, except for very high depletion for the wet-season magnitude (Table 32).

Table 32. Relative alteration for LOI.

Priority Functional Flow Metric	Relative Alteration
Fall Pulse Flow: Magnitude	Depleted, Medium Alteration
Wet-Season Baseflow: Magnitude	Depleted, Medium Alteration
Wet-Season: Median Magnitude	Depleted, Very High Alteration
Peak Flow: Magnitude (2-year flood)	Depleted, Medium Alteration
Peak Flow: Magnitude (5-year flood)	Depleted, Low Alteration
Peak Flow: Magnitude (10-year flood)	Depleted, Low Alteration
Peak Flow: Magnitude of largest storm (Q99)	Depleted, Medium Alteration
Spring Recession Flow: Magnitude	Depleted, Medium Alteration
Dry-Season Baseflow: Magnitude	Depleted, Medium Alteration

3. Probability Threshold: For this example, we evaluated all 3 risk thresholds for steps 4 and 5.
4. Current probabilities: The predicted likelihood (as a probability) of supporting beneficial uses, as represented by CSCI, ASCI, and arroyo toad, based on current hydrologic alteration (delta FFM from step 2) were evaluated (Table 33). For fall pulse flow, spring recession flow, and dry-season baseflow magnitude all probability thresholds were achieved (Table 33). For wet-season median flow and peak flow (10-year flood), probability thresholds were achieved, except for 0.9 threshold for both indices. For the peak flow (2-year flood), probability thresholds were not achieved, except for 0.7 threshold for ASCI. For arroyo toad, which integrated all priority metrics and landscape

characteristics, the overall probability (0.46) did not achieve any of the thresholds. As is, it was hard to interpret if this probability is below the threshold due to current flow alteration or due to landscape characteristics. A webtool is needed to determine if the proposed change in FFM from the project will impact the probability for arroyo toad.

Table 33. Predicted current probabilities for CSCI, ASCI, and arroyo toad.

Priority Functional Flow Metric	Current Probability: CSCI	Current Probability: ASCI	Current Probability: Arroyo Toad	Probability Thresholds Achieved? (0.99, 0.9, 0.7)
Fall Pulse Flow: Magnitude	0.99			Yes
Wet-Season Median: Magnitude	0.93	0.92		Yes, except for 0.99
Peak Flow: Magnitude (2-year flood)		0.81		No, except for 0.7
Peak Flow: Magnitude (10-year flood)	0.97			Yes, except for 0.99
Spring Recession Flow: Magnitude		0.99		Yes
Dry-Season Baseflow: Magnitude	0.99	0.99		Yes
All Magnitude Metrics			0.46	No

5. Current Proximity to Thresholds: The range of acceptable flow alteration across all FFM and indices for the chosen probability threshold was evaluated (Table 34). For wet-season median magnitude and dry-season baseflow, we provided ranges for CSCI and

ASCI. Staff may decide to take the most conservative range of flow alteration for both flow metrics that satisfy both CSCI and ASCI. For example, if the 0.7 probability threshold was chosen, dry-season baseflow magnitude post-project should not increase by more than 3 cfs or decrease by more than 4 cfs to satisfy both CSCI and ASCI.

Table 34. Range of acceptable flow alteration for every FFM, index, and probability threshold.

Index	FFM	Probability Threshold	Range of Acceptable Flow Alteration
ASCI	Dry-Season Baseflow: Magnitude	0.7	Current Delta FFM is within limits. Proposed project should not increase by more than 11 cfs or decrease by more than 4 cfs.
ASCI	Peak Flow: Magnitude (2-year flood)	0.7	Current Delta FFM is within limits. Proposed project should not decrease by more than 129 cfs and can increase by up to 195.47 cfs. However, any increase beyond 195.47 cfs is uncertain.
ASCI	Spring Recession Flow: Magnitude	0.7	Current Delta FFM is within limits. Proposed project should not increase by more than 485 cfs or decrease by more than 173 cfs.
ASCI	Wet-Season Median: Magnitude	0.7	Current Delta FFM is within limits. Proposed project should not increase by more than 34 cfs or decrease by more than 82 cfs.
CSCI	Dry-Season Baseflow: Magnitude	0.7	Current Delta FFM is within limits. Proposed project should not increase by more than 3 cfs or decrease by more than 4 cfs.

Index	FFM	Probability Threshold	Range of Acceptable Flow Alteration
CSCI	Fall Pulse Flow: Magnitude	0.7	Current Delta FFM is within limits. Proposed project should not increase by more than 25 cfs or decrease by more than 58 cfs.
CSCI	Peak Flow: Magnitude (10-year flood)	0.7	Current Delta FFM is within limits. Proposed project should not decrease by more than 2552 cfs and can increase by up to 151.84 cfs. However, any increase beyond 151.84 cfs is uncertain.
CSCI	Wet-Season Median: Magnitude	0.7	Current Delta FFM is within limits. Proposed project should not increase by more than 22 cfs or decrease by more than 96 cfs.
ASCI	Dry-Season Baseflow: Magnitude	0.9	Current Delta FFM is within limits. Proposed project should not increase by more than 4 cfs or decrease by more than 2 cfs.
ASCI	Peak Flow: Magnitude (2-year flood)	0.9	Current Delta FFM is depleted. Proposed project can increase by 87 to 195.47 cfs. However, any increase beyond 195.47 cfs is uncertain.
ASCI	Spring Recession Flow: Magnitude	0.9	Current Delta FFM is within limits. Proposed project should not increase by more than 160 cfs or decrease by more than 57 cfs.
ASCI	Wet-Season Median: Magnitude	0.9	Current Delta FFM is within limits. Proposed project should not increase by more than 12 cfs or decrease by more than 21 cfs.
CSCI	Dry-Season Baseflow: Magnitude	0.9	Current Delta FFM is within limits. Proposed project should not increase

Index	FFM	Probability Threshold	Range of Acceptable Flow Alteration
			by more than 1 cfs or decrease by more than 2 cfs.
CSCI	Fall Pulse Flow: Magnitude	0.9	Current Delta FFM is within limits. Proposed project should not increase by more than 11 cfs or decrease by more than 18 cfs.
CSCI	Peak Flow: Magnitude (10-year flood)	0.9	Current Delta FFM is within limits. Proposed project should not decrease by more than 729 cfs and can increase by up to 151.84 cfs. However, any increase beyond 151.84 cfs is uncertain.
CSCI	Wet-Season Median: Magnitude	0.9	Current Delta FFM is within limits. Proposed project should not increase by more than 9 cfs or decrease by more than 30 cfs.
ASCI	Dry-Season Baseflow: Magnitude	0.99	Current Delta FFM is within limits. Proposed project should not increase by more than 0.51 cfs or decrease by more than 0.46 cfs.
ASCI	Peak Flow: Magnitude (2-year flood)	0.99	Current Delta FFM is depleted. Proposed project can increase by 180 to 195.47 cfs. However, any increase beyond 195.47 cfs is uncertain.
ASCI	Spring Recession Flow: Magnitude	0.99	Current Delta FFM is within limits. Proposed project should not increase by more than 17 cfs or decrease by more than 12 cfs.
ASCI	Wet-Season Median: Magnitude	0.99	Current Delta FFM is within limits. Proposed project should not increase by more than 3 cfs or decrease by more than 0.39 cfs.

Index	FFM	Probability Threshold	Range of Acceptable Flow Alteration
CSCI	Dry-Season Baseflow: Magnitude	0.99	Current Delta FFM is within limits. Proposed project should not increase by more than 0.3 cfs or decrease by more than 0.38 cfs.
CSCI	Fall Pulse Flow: Magnitude	0.99	Current Delta FFM is within limits. Proposed project should not increase by more than 4 cfs or decrease by more than 0.37 cfs.
CSCI	Peak Flow: Magnitude (10-year flood)	0.99	Current Delta FFM is depleted. Proposed project can increase by 47 to 151.84 cfs. However, any increase beyond 151.84 cfs is uncertain.
CSCI	Wet-Season Median: Magnitude	0.99	Current Delta FFM is within limits. Proposed project should not increase by more than 3 cfs or decrease by more than 1 cfs.

6. Compare Project Delta FFM to Range of Acceptable Alteration: In this example, the project proponent indicated that the proposed project will alter the priority functional flow metrics and submitted a table with the project delta FFM values. We compared the project delta FFM values with the range of acceptable flow alteration from step 5 for a chosen probability threshold of 0.7 (Table 35). We also evaluated the general guidance for arroyo toad, however, we could not determine if the project delta FFM will increase or decrease probability without an interactive webtool.

Table 35. Comparison of general guidance for arroyo toad and range of acceptable alteration to project delta FFM. Project delta FFM that exceed the acceptable range are followed by an asterisk.

Priority Functional Flow Metric	Range of Acceptable Flow Alteration (CSCI, ASCI, 0.7 Prob. Threshold)	Project Delta FFM (cfs)	General Guidance for Arroyo Toad	Relative Alteration
Fall Pulse Flow: Magnitude	Current Delta FFM is within limits. Proposed project should not increase by more than 25 cfs or decrease by more than 58 cfs.	1	Reduction tends to increase probability	Depleted
Wet-Season Baseflow: Magnitude		2.7	Reduction tends to increase probability	Depleted
Wet-Season: Median Magnitude	Current Delta FFM is within limits. Proposed project should not increase by more than 22 cfs or decrease by more than 82 cfs.	2	Reduction tends to increase probability	Depleted
Peak Flow: Magnitude (2-year flood)	Current Delta FFM is within limits. Proposed project should not decrease by more than 129 cfs and can increase by up to 195.47 cfs. However, any	52	Unable to determine	Depleted

Priority Functional Flow Metric	Range of Acceptable Flow Alteration (CSCI, ASCI, 0.7 Prob. Threshold)	Project Delta FFM (cfs)	General Guidance for Arroyo Toad	Relative Alteration
	increase beyond 195.47 cfs is uncertain.			
Peak Flow: Magnitude (5-year flood)		88	Increase tends to increase probability	Depleted
Peak Flow: Magnitude (10-year flood)	Current Delta FFM is within limits. Proposed project should not decrease by more than 2552 cfs and can increase by up to 151.84 cfs. However, any increase beyond 151.84 cfs is uncertain.	92	Increase tends to increase probability	Depleted
Peak Flow: Magnitude of largest storm (Q99)		200	Increase tends to increase probability	Depleted
Spring Recession Flow: Magnitude	Current Delta FFM is within limits. Proposed project should not increase by more than 485 cfs or decrease by more than 173 cfs.	20	Increase tends to increase probability	Depleted

Priority Functional Flow Metric	Range of Acceptable Flow Alteration (CSCI, ASCI, 0.7 Prob. Threshold)	Project Delta FFM (cfs)	General Guidance for Arroyo Toad	Relative Alteration
Dry-Season Baseflow: Magnitude	Current Delta FFM is within limits. Proposed project should not increase by more than 3 cfs or decrease by more than 4 cfs.	5*	Reduction tends to increase probability	Depleted

7. Flag FFM at Risk: For CSCI, dry-season baseflow magnitude should be flagged as the project Delta FFM exceeded the range of acceptable flow alteration. Note that an interactive webtool is needed to integrate all project delta FFM into the toad model to determine if the probability for toad will be affected at this site.

Deliverables Submitted:

For more information on the data deliverables, please refer to the ReadMe file at:

<https://sccwrp.sharepoint.com/:w:/s/SDHydroVulnerabilityAssessment/EazVR5ZqwEhJqasBkSSMXxsBUiKaa0kJB53GLDMkD9PAmg?e=Wgn0ND>.

All data products (csv, kml, and shapefile) can be downloaded at:

<https://sccwrp.sharepoint.com/:f:/s/SDHydroVulnerabilityAssessment/EnTKAUjiMypApbcw4RtMVtUBtSLiwtesSqF8r3l7V9lrw?e=G4TeU>.

We also hosted a training and demonstration for Water Board staff on March 13, 2023. The meeting presentation can be downloaded at:

<https://sccwrp.sharepoint.com/:f:/s/SDHydroVulnerabilityAssessment/EgmsCseAFoFLt4hLq8GaNj8BzT1FCQaEXpC8VpDOAY-F4g?e=PGI3aL>.

NEXT STEPS

This study developed hydrologic and ecological models that were used to evaluate hydrologic risk of current flow conditions on aquatic life. Next steps for a future phase of this study could include:

- Evaluation of low flow measurement methods and refinement of the dry-season baseflow magnitude models, incorporating shallow groundwater contributions
- Integration of future climate scenarios and effects on functional flows and biology (CSCI, ASCI, and arroyo toad), including scenarios characterizing amplified swings of extremely dry years and wet years
- Refinements to the arroyo toad model, focusing on changes to populations over time
- Development of an interactive webtool for the decision framework, including integration of proposed project changes and other future scenarios

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APPENDIX A. INPUT VARIABLES FOR HYDROLOGIC RANDOM FOREST MODELS

Table A1. Predictor variables for functional flow metric delta random forest models. Table adapted from Grantham et al. (2022).

DESCRIPTION	VARIABLE	DATA SOURCE
Monthly precipitation for water year (mm)	ppt_Oct_wy - ppt_Sep_wy	PRISM Climate Group 2017
Seasonal precipitation for water year (mm)	ppt_fall_wy - ppt_summer_wy	PRISM Climate Group 2017
Annual precipitation for water year (mm)	ppt_ann_wy	PRISM Climate Group 2017
Monthly precipitation in previous water year (mm)	ppt_Oct_pwy - ppt_Sep_pwy	PRISM Climate Group 2017
Seasonal precipitation for previous water year (mm)	ppt_wint_pwy - ppt_summer_pwy	PRISM Climate Group 2017
Annual precipitation for previous water year (mm)	ppt_ann_pwy	PRISM Climate Group 2017
Monthly average temperature in water year (deg C)	tav_Oct_wy - tav_Sep_wy	PRISM Climate Group 2017
Seasonal average temperature for water year (deg C)	tav_fall_wy - tav_summer_wy	PRISM Climate Group 2017
Annual average temperature for water year (deg C)	tav_ann_wy	PRISM Climate Group 2017
Monthly average temperature in previous water year (deg C)	tav_Oct_pwy - tav_Sep_pwy	PRISM Climate Group 2017
Seasonal average temperature for previous water year (deg C)	tav_winter_pwy - tav_summer_pwy	PRISM Climate Group 2017
Annual average temperature for previous water year (deg C)	tav_ann_pwy	PRISM Climate Group 2017

DESCRIPTION	VARIABLE	DATA SOURCE
Mean average annual precipitation (mm), derived from 1950-2015 PRISM data.	Ann_AVGPrecip	PRISM Climate Group 2017
Maximum average annual precipitation (mm), derived from 1950-2015 PRISM data.	Ann_MaxPrecip	PRISM Climate Group 2017
Minimum average annual precipitation (mm), derived from 1950-2015 PRISM data.	Ann_MinPrecip	PRISM Climate Group 2017
Minimum average annual air temperature (degrees C), derived from 1950-2015 PRISM data	T_MIN_ann	PRISM Climate Group 2017
Mean annual air temperature (degrees C), derived from 1950-2015 PRISM data	T_MEAN_ann	PRISM Climate Group 2017
Maximum average monthly air temperature (degrees C), derived from 1950-2015 PRISM data	T_MAX_mon	PRISM Climate Group 2017
Minimum average monthly air temperature (degrees C), derived from 1950-2015 PRISM data	T_MIN_ann	PRISM Climate Group 2017
Drainage area of basin (square kilometers)	DRAIN_SQKM	Horizon Systems 2012
Mean basin slope (percent)	SLOPE_PCT_30M	Horizon Systems 2012
Mean basin elevation (meters)	ELEV_MEAN_M_BASIN_30M	Horizon Systems 2012
Minimum basin elevation (meters)	ELEV_MIN_M_BASIN_30M	Horizon Systems 2012
Maximum basin elevation (meters)	ELEV_MAX_M_BASIN_30M	Horizon Systems 2012

DESCRIPTION	VARIABLE	DATA SOURCE
Difference between maximum and minimum basin elevation (meters)	ElvRng	Horizon Systems 2012
Proportion of basin occupied by HLR (proportion)	HLR 1 - 20	Wolock 2003a
Subsurface flow contact time index	CONTACT	Falcone 2011
Base Flow Index (BFI) is a ratio of base flow to total streamflow (percentage)	BFI_AVE	Falcone 2011
Topographic wetness index	TOPWET	Falcone 2011
Dunne overland flow (percentage)	PERDUN	Falcone 2011
Rainfall and Runoff factor ("R factor" of Universal Soil Loss Equation); average annual value for period 1971-2000	RFACT	Falcone 2011
Horton overland flow (percentage)	PERHOR	Falcone 2011
Average value of depth to seasonally high water table (feet)	DEPTH_WATTAB	Falcone 2011
Average value of silt content (percentage)	SILTAVE	Falcone 2011
Average value of clay content (percentage)	CLAYAVE	Falcone 2011
Average value of sand content (percentage)	SANDAVE	Falcone 2011
Percentage of soils in hydrologic group A (high infiltration rates)	HGA	Falcone 2011
Percentage of soils in hydrologic group B (moderate infiltration rates)	HGB	Falcone 2011
Percentage of soils in hydrologic group C (slow soil infiltration rates)	HGC	Falcone 2011

DESCRIPTION	VARIABLE	DATA SOURCE
Percentage of soils in hydrologic group D (very slow infiltration rates)	HGD	Falcone 2011
Average K-factor value (erodibility factor) for the uppermost soil horizon in each soil component	KFACT_UP	Falcone 2011
Average value of percent by weight of soil material less than 3 inches in size and passing a No. 10 sieve (2 mm)	NO10AVE	Falcone 2011
Average value of percent by weight of soil material less than 3 inches in size and passing a No. 200 sieve (.074 mm)	NO200AVE	Falcone 2011
Average value of percent by weight of soil material less than 3 inches in size and passing a No. 4 sieve (5 mm)	NO4AVE	Falcone 2011
Average value of organic matter content (percent by weight)	OMAVE	Falcone 2011
Average permeability (inches/hour)	PERMAVE	Falcone 2011
Average value of total soil thickness examined (inches)	ROCKDEPAVE	Falcone 2011
Average value for the range of available water capacity for the soil layer (inches of water per inches of soil depth)	AWCAVE	Falcone 2011
Average value of depth to seasonally high water table (feet)	WTDEPAVE	Falcone 2011
Average value of bulk density (grams per cubic centimeter)	BDAVE	Falcone 2011
Max value of bulk density (grams per cubic centimeter)	BDMAX	Falcone 2011

DESCRIPTION	VARIABLE	DATA SOURCE
Percent of watershed composed of geology class according to Reed & Bush (2001)	granitic	Falcone 2011
Percent of watershed composed of geology class according to Reed & Bush (2001)	sedimentary	Falcone 2011
Percent of watershed composed of geology class according to Reed & Bush (2001)	volcanic	Falcone 2011
Deposits of mountain glaciers	SGEO8	Falcone 2011
Micaceous residuum without much quartz; clay, mostly kaolinite	SGEO21	Falcone 2011
Bouldery and sandy colluvium on granitic rocks	SGEO44	Falcone 2011
Clayey and loamy colluvium; on poorly consolidated rocks on lee sides of Pacific Coast Ranges	SGEO45	Falcone 2011
Mean watershed percent Potassium Oxide concentration of lithology (percent)	KO_pct	Olson and Hawkins 2014
Mean watershed percent Calcium Oxide concentration of lithology (percent)	CaO_pct	Olson and Hawkins 2014
Mean watershed percent Iron Oxide concentration of lithology (percent)	FeO_pct	Olson and Hawkins 2014
Mean watershed percent Magnesium Oxide concentration of lithology (percent)	MgO_pct	Olson and Hawkins 2014
Mean watershed percent Phosphorus concentration of lithology (percent)	P_pct	Olson and Hawkins 2014

DESCRIPTION	VARIABLE	DATA SOURCE
Mean watershed percent Sulfur concentration of lithology (percent)	S_pct	Olson and Hawkins 2014
Mean watershed percent Silica Oxide concentration of lithology (percent)	SiO_pct	Olson and Hawkins 2014
Mean watershed Rock Uniaxial Compressive Strength (megaPascals)	UCS	Olson and Hawkins 2014
Mean watershed rock hydraulic conductivity ($\times 10^6$ meters / second)	Lperm	Olson and Hawkins 2014
Mean watershed annual natural groundwater recharge (days)	RECHARGE	Wolock 2003b
Percent of watershed area classified as crop land use (NLCD 2011 class 82)	PctCrop2011Ws	Hill et al. 2016
Percent of catchment area classified as developed, low-intensity land use (NLCD 2006 class 22)	PctUrbLo2006Cat	Hill et al. 2016
Percent of catchment area classified as developed, medium-intensity land use (NLCD 2006 class 23)	PctUrbMd2006Cat	Hill et al. 2016
Percent of catchment area classified as developed, high-intensity land use (NLCD 2006 class 24)	PctUrbHi2006Cat	Hill et al. 2016
Mean population density (people/square km) within catchment	PopDen2010Cat	Hill et al. 2016
Total possible volume of all reservoirs per unit area of watershed (cubic meters/square km) based on the National Inventory of Dams (https://catalog.data.gov/dataset/national-inventory-of-dams)	DamNIDStorWs	Hill et al. 2016

DESCRIPTION	VARIABLE	DATA SOURCE
Density of georeferenced dams within watershed (dams/ square km) based on the National Inventory of Dams	DamDensWs	Hill et al. 2016

Data Source References

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APPENDIX B. CALCULATING FUNCTIONAL FLOW METRICS (FFM)

The functional flows calculator (FFC) is a computational tool that calculates the functional flow metrics for a given daily time series data. This appendix describes resource links and general guidance for using the FFC on the eflows website and in R or Python coding environments adapted from California Environmental Flows Framework (CEFF) Appendix K by Patterson et al. 2021 (see <https://ceff.ucdavis.edu/tech-report>, Technical Report Appendices, March 2021).

Resource Links

Table B1. Links to helpful FFC documentation and tutorials.

Resource	Link	Description
eFlows website	https://eflows.ucdavis.edu/hydrology	Website with capability to explore California's natural hydrology, geomorphology, and ecology. The hydrology feature includes reference-condition flow data for 223 gage sites across California that can be visualized and downloaded. Users can also upload and analyze their own streamflow data with the eFlows web tool, described below.
eFlows website documentation	https://eflows.gitbook.io/project/	Webpage describing the content of the eFlows website, including the hydrologic classification, hydrograph visualizations, and functional flow metrics.
Functional flow metric documentation	https://eflow.gitbook.io/ffc-readme/	In-depth description of each functional flow metric, how it is calculated, and steps for calculation including snippets from the Python source code.
Webinar tutorial	https://www.youtube.com/watch?v=iIF3mBGEJag	This webinar tutorial covers how to perform functional flow analysis of user-uploaded streamflow data using either the eFlows website interface, or the source code in the Python programming language.

Resource	Link	Description
Python Code repository	https://github.com/leogoesger/func-flow	Code repository including all scripts and data for running the functional flows calculator source code in the Python programming language, including a catalog of all updates made to the code.
FFC API package in R	https://github.com/ceff-tech/ffc_api_client	The FFC API R package extracts functional flow metrics based on the python source code to assess hydrologic alteration.
Peer-reviewed literature, Patterson et al. 2020	https://www.researchgate.net/publication/339632311_A_hydrologic_feature_detection_algorithm_to_quantify_seasonal_components_of_flow_regimes	Peer-reviewed article in the Journal of Hydrology describing the scientific background and methodology of the functional flows calculator for streamflow analysis.
Natural Flows Database	https://rivers.codefornature.org/#/home	Reference or unimpaired functional flow metric predictions for every COMID in the CA can be downloaded at the Natural Flows Database.

Table B2. Summary of functional flow metrics.

Functional Flow Metric Name	Unit	Functional Flow Metric Description
Fall pulse magnitude	cfs	Peak magnitude of fall pulse event (maximum daily peak flow during event)
Fall pulse timing	water year day (Oct 1=1)	Water year day of fall pulse event peak
Fall pulse duration	days	Duration of fall pulse event
Wet-season baseflow and wet-season median flow	cfs	Magnitude of wet-season flows (10th percentile and median of daily flows within that season, including peak flow events)
Wet-season timing	water year day	Start date of wet season in water year days
Wet-season duration	days	Wet-season duration (# of days from start of wet-season to start of spring season)
2-year, 5-year, and 10-year flood magnitude	cfs	2-year, 5-year, and 10-year recurrence interval peak flow
2-year, 5-year, and 10-year flood duration	days	Seasonal duration of 2-year, 5-year, and 10-year recurrence interval peak flow (cumulative number of days in which this peak flow magnitude is exceeded)
2-year, 5-year, and 10-year flood frequency	occurrences	Frequency of 2-year, 5-year, and 10-year recurrence interval peak flow within a season
Spring recession magnitude	cfs	Spring recession magnitude (daily flow on start date of spring-flow period, 4 days after last wet-season peak)
Spring timing	water year day	Start date of spring in water year days

Functional Flow Metric Name	Unit	Functional Flow Metric Description
Spring duration	days	Spring flow recession duration (# of days from start of spring to start of dry-season baseflow period)
Spring rate of change	percent	Spring flow recession rate (median daily rate of change over decreasing periods during the recession)
Dry-season baseflow and high baseflow	cfs	50th and 90th percentile of daily flow within dry season
Dry-season timing	water year day	Dry-season baseflow start timing (water year day of dry season)
Dry-season duration	days	Dry-season duration (# of days from start of dry season to start of wet season)

Using eFlows for data analysis

Users can analyze their own daily modeled or observed streamflow data on the eFlows website, with options to download data and visualizations. Users must first create a profile on the eFlows website, available in the top-right corner of the Hydrology main page (Figure B1).

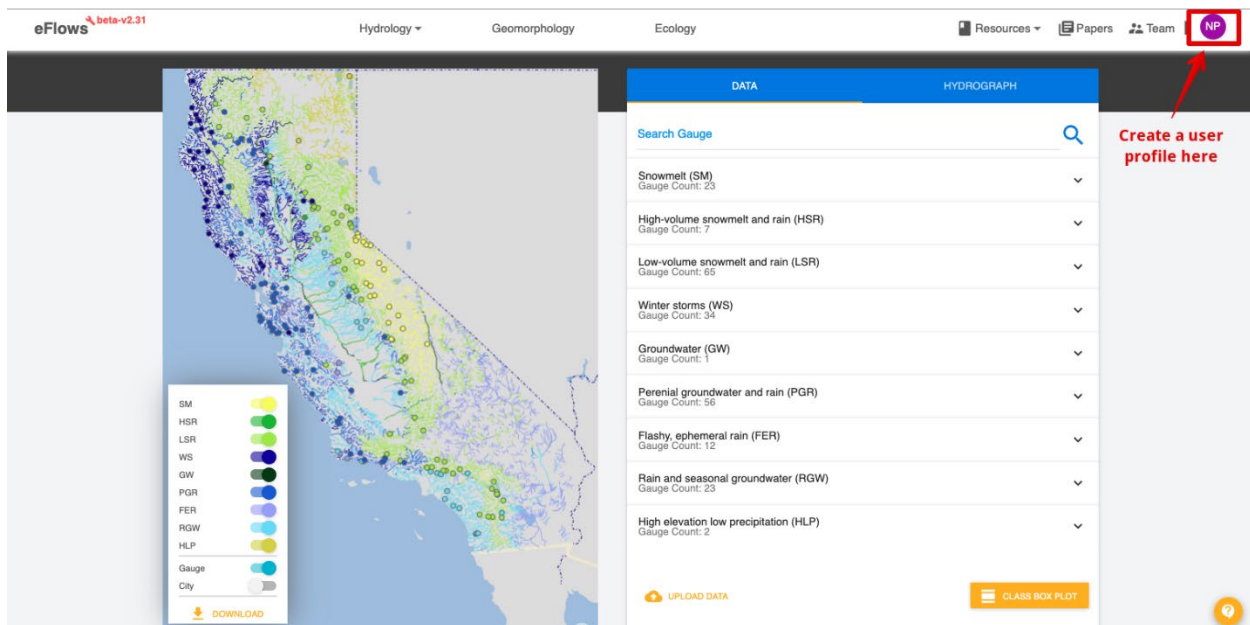


Figure B1. User profile button is highlighted in the top-right corner of the Hydrology main page. Creating a user profile is necessary to upload data to the website.

Data Upload

Once a user profile is created, users can navigate to the profile page, where flow data can be uploaded for analysis with the FFC (Figure B2). User data must be in comma-separated values (csv) format and files can be selected using the “Pick a File” button on the profile page. Once selected, names can be defined for the file, the river, and the location, and the water year can be set to any calendar value (default value is October 1st). The start date of the water year affects calculation of functional flow metrics, and October 1st is recommended as the start date for any analyses in California or regions that exhibit a similar Mediterranean climate. Uploaded data must have a specific two-column format with date in mm/dd/yyyy format and flow in cubic feet per second (cfs). Additionally, headers must have the exact names: date and flow. If these requirements are not met, the data will not upload successfully. Please view the Youtube tutorial in the Resources tab for step-by-step instructions for uploading data (Table B1, webinar tutorial).

Welcome, Noelle

Upload your time series data here. The application requires a commas separated values (.csv) file with two columns: column 1 contains dates (mm/dd/yyyy) and column 2 contains the corresponding daily flow (cfs). The columns must have the following exact headers: **date** for the dates column and the **flow** for the flow column. Any gaps in the data will be interpolated. Please download [this sample csv file](#) for a data format example. Tool is under development for user uploaded streamflow data, please use results with caution.

Water Year Start Date
10/1

Name your uploaded data

PICK A FILE

River Name (optional)

Location (optional)

PARAMS (OPTIONAL)

UPLOAD

Figure B2. Profile page for user-uploaded streamflow data.

Outputs from FFC Analysis

Files generated by the FFC available to download for user-uploaded streamflow data are the same as those available for reference gages, as described in Data Downloads above.

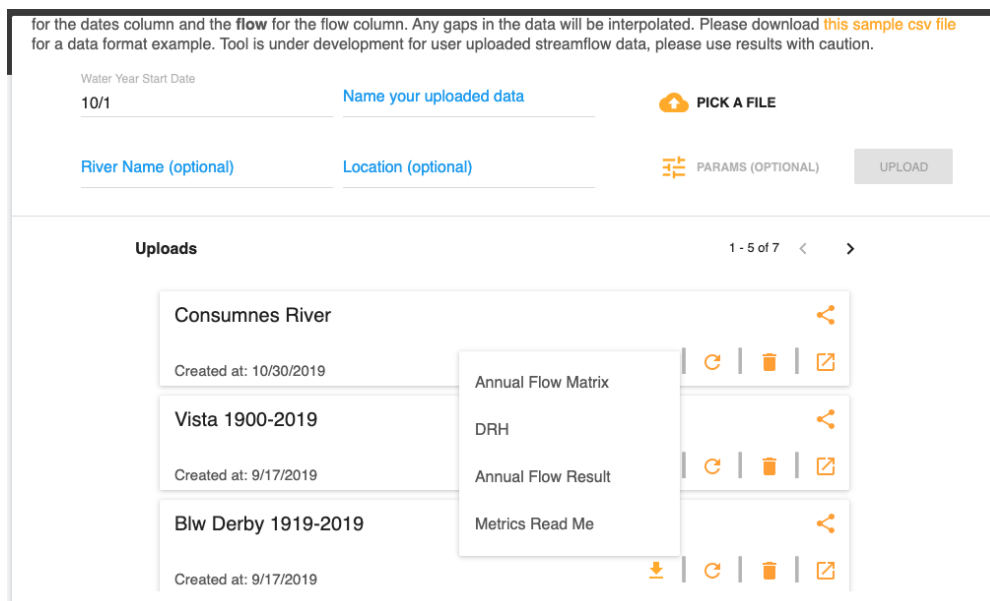


Figure B3. Files available for download from the FFC after processing user-uploaded flow data.

In addition to generating downloadable files, the web tool also allows users to view their uploaded data interactively on the website. By clicking on the name of the uploaded data from the “Uploads” list on the user profile page (Figure B3), the user is taken to a page showing hydrograph visualizations of the uploaded data. Visualizations include a gage DRH, which can be overlaid with the DRH from a class or gage from the California reference flow dataset (Figure B4). Visualization options also include annual flow plot (top-left, Figure B4), which can be viewed with flow metrics overlaid (Figure B5).

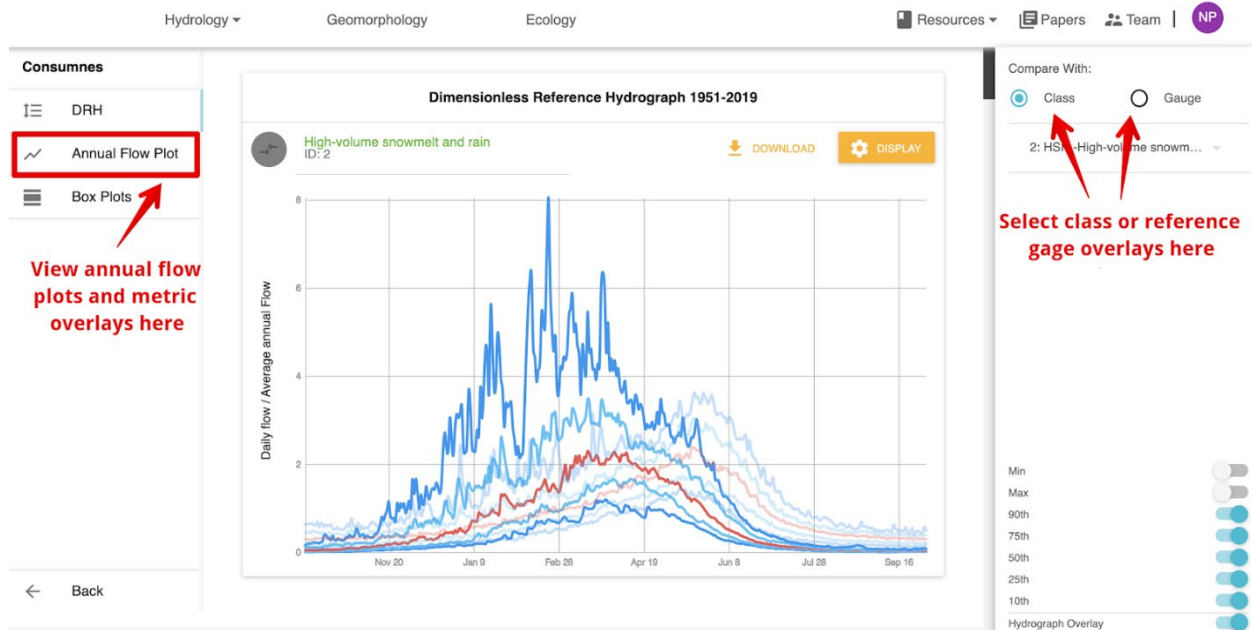


Figure B4. User uploaded data visualized as a DRH, overlaid with a DRH from the California natural stream classes.

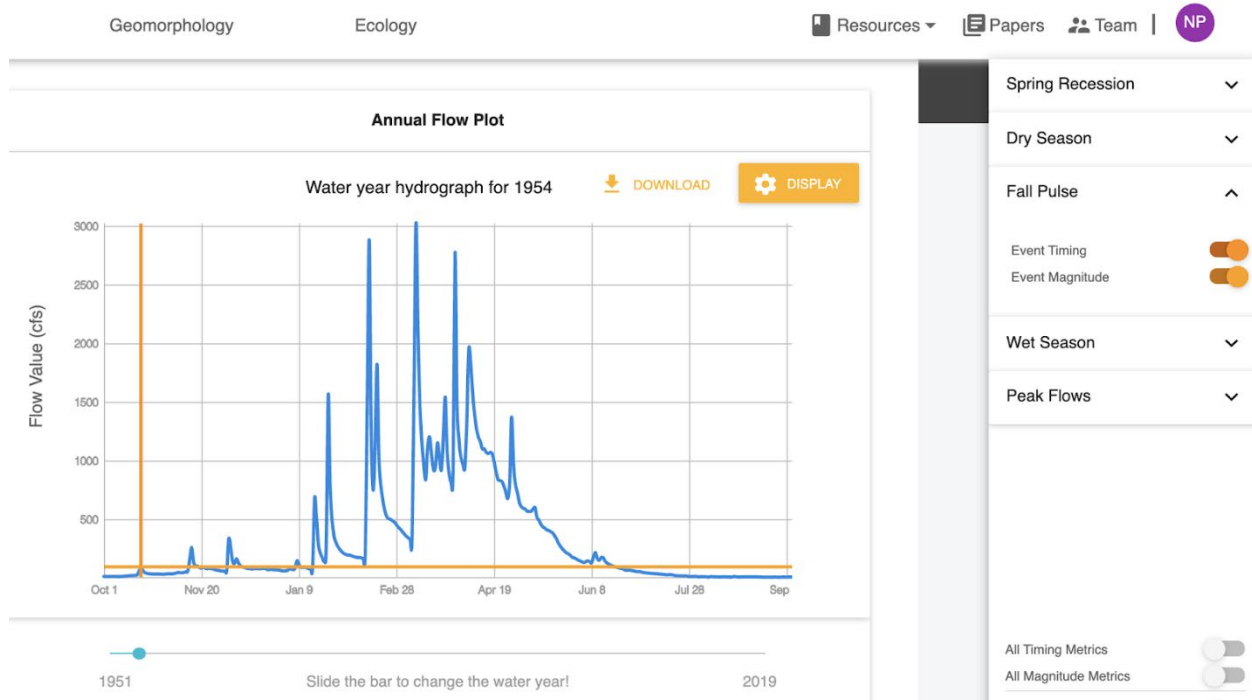


Figure B5. User uploaded data visualized in annual daily hydrographs, with metric values optionally displayed.

FFC Source Code

Advanced users can use the FFC directly from the source code in both Python and R. Using the source code is recommended for users highly proficient in programming or willing to invest time to become familiar with the programming environments.

Guidance for using the python source code is available in a webinar tutorial:

<https://www.youtube.com/watch?v=iIF3mBGEJag>.

An R package is available to extract functional flow metrics based on this python source code and to assess hydrologic alteration: https://github.com/ceff-tech/ffc_api_client. Additional details on setting up and using the R package can be found here:

https://ceff.sf.ucdavis.edu/sites/g/files/dgvnsk5566/files/media/documents/07_FunctionalFlowsCalculator_RPackage_demo_KTQ_v2_0.pdf

Additionally, reference or unimpaired functional flow metric predictions for every COMID in the state can be downloaded at the Natural Flows Database:

<https://rivers.codefornature.org/#/home>

APPENDIX C. DECISION FRAMEWORK EXAMPLE 2 WITH DETAILED WATERSHED MODEL OF CURRENT AND REFERENCE HYDROLOGY

This appendix provides an example of the decision framework steps if a detailed watershed model of current and reference conditions is available. This example uses a hypothetical stream reach and modeled hydrologic data. The steps outlined in this example would ideally be done automatically with a webtool. Additionally, a webtool is needed to evaluate the probability of supporting arroyo toad. We therefore only focused on CSCI and ASCI in the example below.

Example 2: Do have detailed watershed model of reference and current conditions (step 2 is “yes”)

1. Location of interest: The hypothetical project discharged into a hypothetical stream reach and has the potential to affect COMID 12345678.
2. Watershed model: There was an existing watershed model of reference and current conditions readily available that has lower model uncertainty compared to the regional random forest models developed in this study. The watershed model produced a timeseries of 15 continuous years of daily flow data from water years 2000 to 2015 under current conditions and a hypothetical reference, unimpaired condition. Following

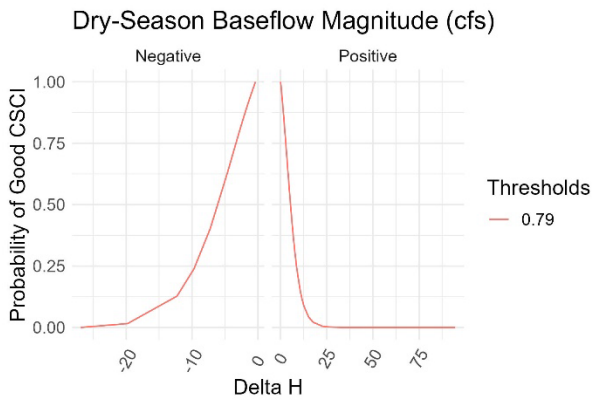
directions in Appendix B, functional flow metrics were calculated for the current and reference scenarios. Next, we calculated the delta FFM as current FFM minus reference FFM for every year. We then calculated the median delta FFM values across all years for each metric. We only used the median delta FFM for priority FFM for CSCI and ASCI for project review (Table C1).

Table C1. Median Delta FFM for priority metrics at LOI.

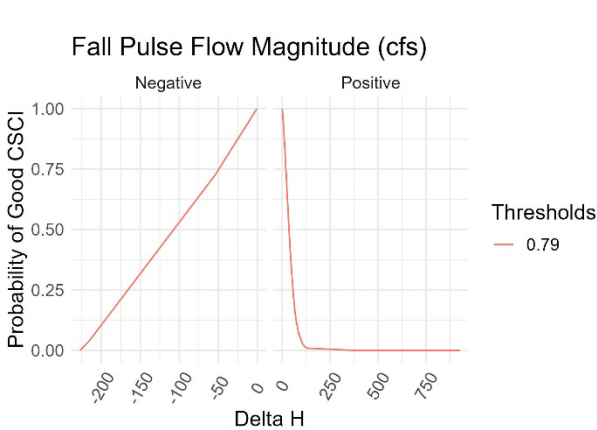
Priority Functional Flow Metric	Delta FFM
Dry-Season Baseflow: Duration	19 days
Dry-Season Baseflow: Magnitude	0.05 cfs
Fall Pulse Flow: Magnitude	23.4 cfs
Peak Flow: Magnitude (10-year flood)	59.7 cfs
Peak Flow: Magnitude (2-year flood)	36.8 cfs
Spring Recession Flow: Duration	-42.5 days
Spring Recession Flow: Magnitude	26.4 cfs
Spring Recession Flow: Timing	0
Wet-Season: Median Magnitude	0.62 cfs

3. Probability Threshold: For this example, we used the 0.9 probability (risk) threshold.
4. Current probabilities: A webtool is needed to predict the current likelihood (as a probability) of supporting beneficial uses based on the delta FFM from Table B1. If inclined, the regional curves for CSCI and ASCI (Figure C1) could be used to make a rough estimation of current probability by finding the delta FFM on the x-axis of the curve and determining the intersection to the curve. Treat this step as purely exploratory – the proximity to threshold from step 5 will provide a more precise way of evaluating if the FFM is below or above the 0.9 risk threshold.

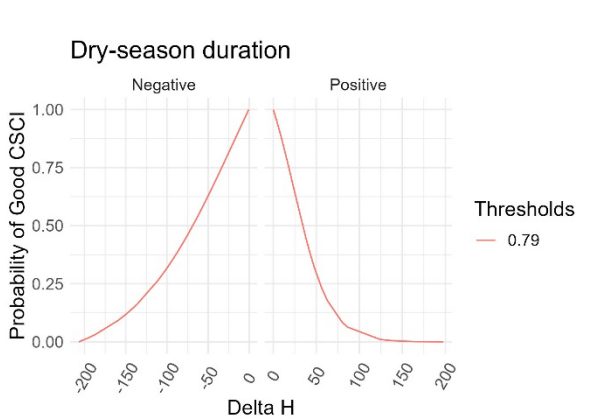
A. CSCI



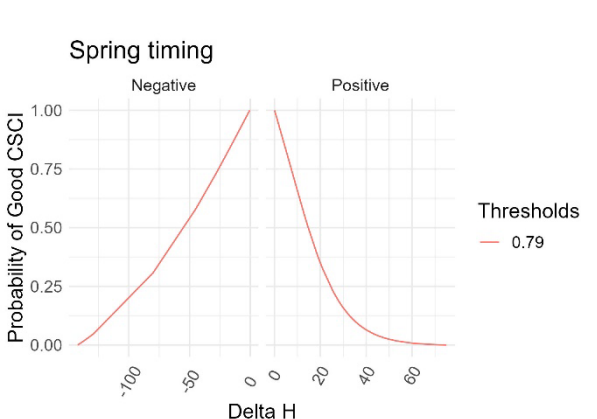
B. CSCI



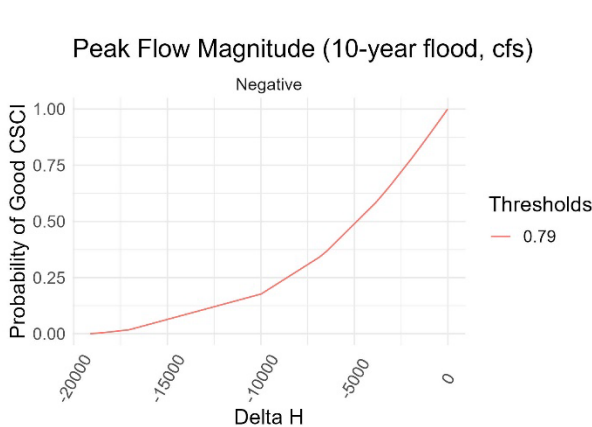
C. CSCI



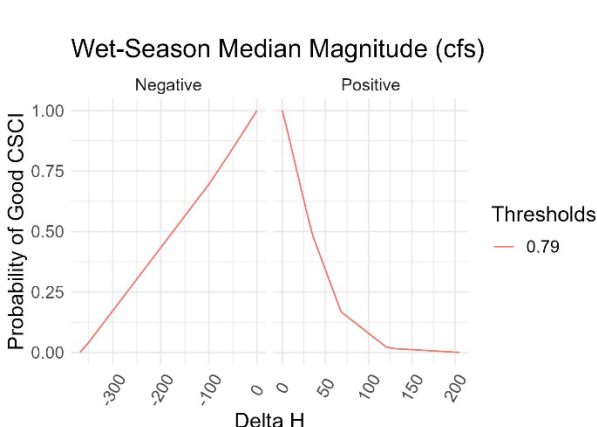
D. CSCI



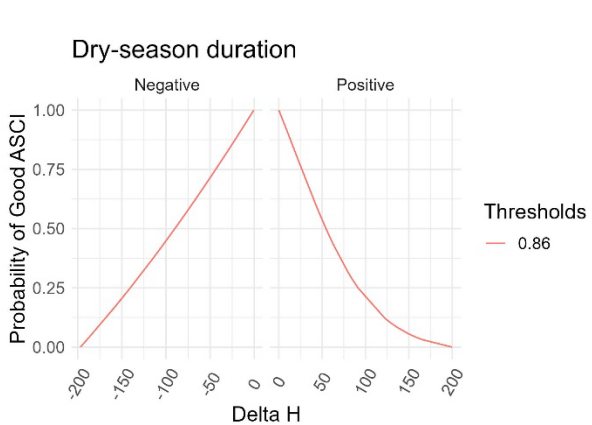
E. CSCI



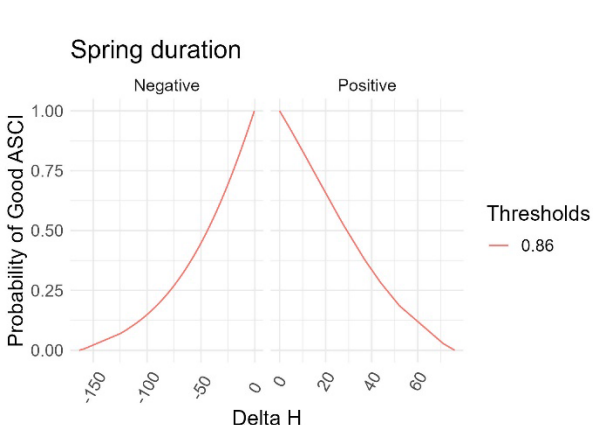
F. CSCI



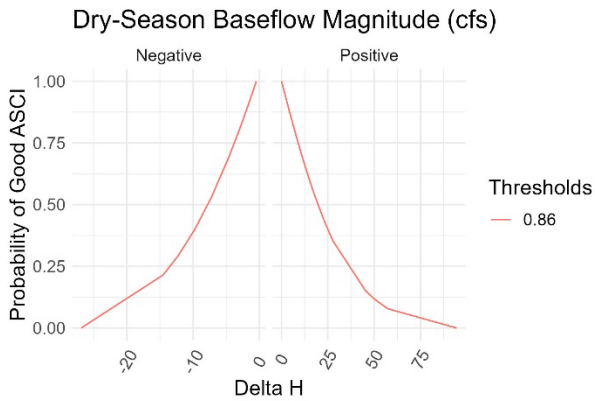
G. ASCI



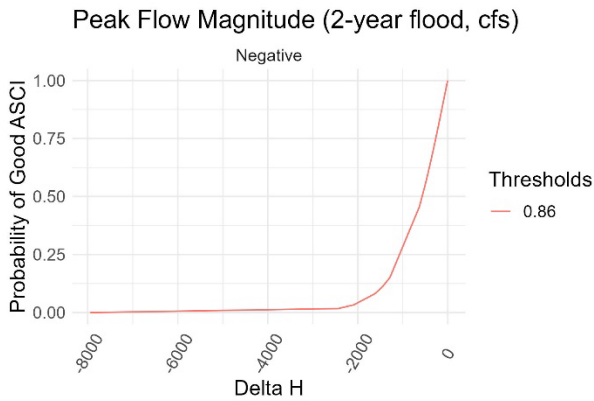
H. ASCI



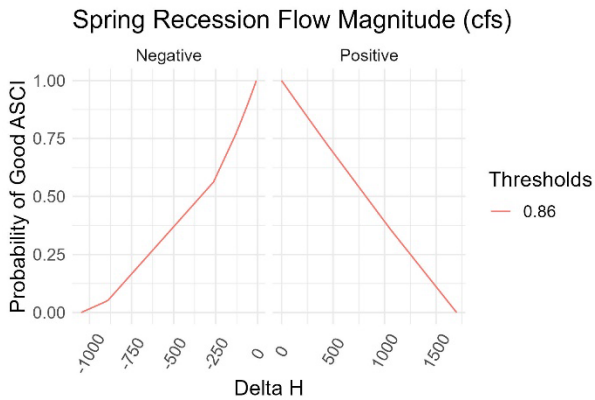
I.



J.



K.



L.

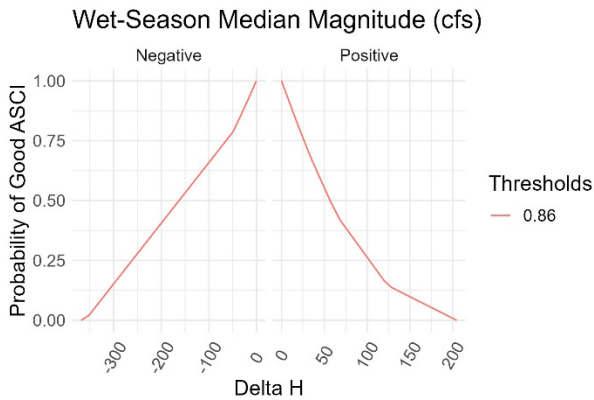


Figure C1. Flow ecology curves for the six respective FFMs chosen for each biological index: A) Dry-Season Baseflow Magnitude for CSCI; B) Fall Pulse Flow Magnitude for CSCI; C) Dry-Season Duration for CSCI; D) Spring Timing for CSCI; E) Peak Flow Magnitude, 10-Year Flood for CSCI; F) Wet-Season Median Magnitude for CSCI; G) Dry-Season Duration for ASCI; H) Spring Duration for ASCI; I) Dry-Season Baseflow Magnitude for ASCI; J) Peak Flow Magnitude, 2-Year Flood for ASCI; K) Spring Recession Flow Magnitude for ASCI; and L) Wet-Season Median Magnitude for ASCI.

5. Current Proximity to Thresholds: We used the delta FFM from step 2 to determine if the current delta FFM is within, above, or below each delta FFM limit from Tables 2 and 3 in the main document. For ASCI and CSCI dry-season baseflow magnitude, for example, the regional delta FFM limit (change from reference to current) for 0.9 probability is from -1.73 cfs to 3.53 cfs and -1.64 to 1.25 cfs, respectively. The current delta FFM for dry-season baseflow magnitude is 0.05 cfs , indicating that this delta FFM falls within the delta FFM limit for both ASCI and CSCI. The current proximity to threshold was calculated by: current delta FFM – upper limit and current delta FFM – lower limit for every priority metric and threshold to determine the current range of acceptable flow alteration a site can endure by a proposed project (Table C2).

Table C2. Range of acceptable flow alteration for every FFM, index, and probability threshold.

Index	FFM	Probability Threshold	Delta FFM	Range of Acceptable Flow Alteration by Project
ASCI	Dry-Season Baseflow: Duration	0.9	19 days	Current Delta FFM is augmented (long). Proposed project can decrease duration by 8 days to 36 days.
ASCI	Spring Recession Flow: Duration	0.9	-42.5 days	Current Delta FFM is depleted (short). Proposed project can increase duration by 35 days to 49 days.
ASCI	Dry-Season Baseflow: Magnitude	0.9	0.05 cfs	Current Delta FFM is within limits. Proposed project should not increase by more than 3 cfs or decrease by more than 2 cfs.
ASCI	Peak Flow: Magnitude (2-year flood)	0.9	36.8 cfs	Not enough data for flow ecology curve peak augmentation.
ASCI	Spring Recession	0.9	26.4 cfs	Current Delta FFM is within limits. Proposed project should not increase

Index	FFM	Probability Threshold	Delta FFM	Range of Acceptable Flow Alteration by Project
	Flow: Magnitude			by more than 133 cfs or decrease by more than 85 cfs.
ASCI	Wet-Season: Median Magnitude	0.9	0.62 cfs	Current Delta FFM is within limits. Proposed project should not increase by more than 10 cfs or decrease by more than 23 cfs.
CSCI	Dry-Season Baseflow: Duration	0.9	19 days	Current Delta FFM is augmented (long). Proposed project can decrease duration by 11 days to 33 days.
CSCI	Dry-Season Baseflow: Magnitude	0.9	0.05 cfs	Current Delta FFM is within limits. Proposed project should not increase by more than 1 cfs or decrease by more than 2 cfs.
CSCI	Fall Pulse Flow: Magnitude	0.9	23.4 cfs	Current Delta FFM is augmented. Proposed project can decrease by 14 to 43 cfs.
CSCI	Peak Flow: Magnitude (10-year flood)	0.9	59.7 cfs	Not enough data for flow ecology curve peak augmentation.
CSCI	Wet-Season: Median Magnitude	0.9	0.62 cfs	Current Delta FFM is within limits. Proposed project should not increase by more than 6 cfs or decrease by more than 33 cfs.
CSCI	Spring Recession Flow: Timing	0.9	0	Current Delta FFM is within limits. Proposed project should not change timing by more than 3 days later or by more than 11 days earlier.

6. Compare Project Delta FFM to Range of Acceptable Alteration: In this example, the project proponent indicated that the proposed project will increase all of the magnitude metrics by 2 cfs and will likely not change the duration and timing metrics. We compared the project delta FFM of +2 cfs with the range of acceptable flow alteration from step 5 Table C2. The +2 cfs will likely affect the dry-season baseflow magnitude, which is currently within limits but post-project will be pushed below the 0.9 risk threshold for CSCI. Note that the peak magnitude metrics (2-year and 10-year floods) are both currently higher than reference expectations. However, there was not enough data for the flow-ecology curve peak augmentation to determine range of acceptable alteration for CSCI and ASCI and therefore any increase is uncertain.
7. Flag FFM at Risk: For CSCI, the dry-season baseflow magnitude should be flagged as the project Delta FFM (+2 cfs) exceeds the range of acceptable flow alteration.