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Final Work Plan

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Introduction and Project Objectives

Providing the science to develop numeric flow criteria has the potential to be a powerful tool for use in emerging regulatory programs such as freshwater Bioobjectives, hydromodification management, and nutrient numeric endpoints. Flow criteria (defined by hydrologic and hydraulic metrics) must in turn be related to biological endpoints, such as benthic communities. Instream biota are well established as a measure of stream condition because they integrate the consequences of stressors over time and thus provide opportune indicators of general environmental health (Karr 1999, Karr and Chu 1999). Benthic macroinvertebrates are the most commonly used bioindicator in streams because of their well-studied life histories, relatively sessile nature, available taxonomy and relative ease of collection and identification (relative to other instream organisms). The same characteristics that have made benthic invertebrates attractive for routine monitoring and assessment also make them useful for establishing regulatory standards or benchmarks because biological criteria are more closely related to the designated uses of waterbodies than are physical or chemical measurements (NRC 2001).

Use of biological endpoints for regulatory or compliance purposes requires the ability to relate specific stressors to key biological metrics and to use this understanding to influence management actions intended to improve condition or mitigate stressors. Stressors can be physical, chemical, or hydrological. For benthic invertebrates, altered hydrology is one of the primary factors that directly or indirectly affect the health of instream communities (Konrad et al. 2008, Brooks et al. 2011).

Many studies have demonstrated that alterations of flow regime can be associated with changes in macroinvertebrate assemblages (Pringle et al. 2000, Miller et al. 2007, Poff & Zimmerman 2010). Although a basic understanding of the relationship between flow alteration and ecological response exists, few studies have provided the mechanistic evidence on how specific ecological metrics respond to various degrees of flow alteration that is necessary for establishing objectives or standards.

The goal of the this project is to develop an approach for establishing instream environmental flow requirements necessary to meet ecological benchmarks as defined by measures of benthic macroinvertebrate community composition and structure. These requirements can then be used to help establish criteria for use in hydromodification management, nutrient numeric endpoints, and freshwater Bioobjectives. This project will address the following questions: 1) how should streams in California be grouped or classified for the purposes of establishing environmental flow requirements; 2) what are the key hydrologic or hydraulic variables that should be used for environmental flow requirements; 3) what are the key biological response variables that should be used when establishing environmental flow requirements; 4) what is the appropriate framework/approach for setting actual flow requirements for specific stream types.
General Study Approach

The *ecological limits of hydrologic alteration* (ELOHA) framework provides a synthesis of a number of existing hydrologic techniques and environmental flow methods that are currently being used to various degrees and that can support comprehensive regional flow management (Figure 1; Poff et al. 2010). A key element in the ELOHA framework is defining relationships between altered flow and ecological characteristics that can be empirically tested with existing and newly collected field data. The ELOHA framework links geomorphic classification, hydrologic analysis, and ecological response predictions to help determine environmental flow standards necessary to meet scientific and management objectives that will protect stream reaches from a particular level of risk of ecosystem degradation.

**Figure 1: Ecological limits of hydrologic alteration (ELOHA) framework**

This project will apply the ELOHA framework to California’s wadeable streams to support development of numeric flow criteria. The general approach will consist of the following tasks:

1. Classify stream reaches based on geomorphic and long-term flow characteristics
2. Identify metrics that reflect differences in flow characteristics based on both natural patterns and anthropogenic effects
3. Develop predictive tools that can be used in ungaged areas to differentiate reference vs. non-reference conditions
4. Relate changes in flow to geomorphic or hydraulic changes
5. Identify biological metrics most sensitive flow or hydraulic changes for various stream types
6. Develop flow–ecology relationships that relate flow and hydraulic parameters to instream biological community structure across a gradient of disturbance
7. Develop tools that can predict changes in flow and then biology associated with changes in land use or land management (local). Tools will be:
   a. Driven by data density
   b. Exportable to other areas
8. Demonstrate application of flow-ecology framework in one or more pilot watersheds

Study boundary

The initial hydrologic classification will cover all gaged streams in California. Similarly, evaluation of candidate biological metrics will be done at the statewide scale to take advantage of the large amount of available bioassessment data. Intensive modeling and localized flow-ecology relationships will be done at the watershed scale with a focus on demonstrating relationships in selected southern California watersheds.

Study Tasks

Task 1: Classify Streams based on Natural Hydroclimatic and Physical Characteristics

Purpose

The purpose of a natural classification is to aid in understanding how a stream's natural characteristics and setting influence the relationship between flow and biology. Different types of streams may be expected to respond differently to flow alteration (i.e. may be more or less sensitive to different alterations). The classification system is a first step in establishing expectations about relative responses of stream biotic communities to anthropogenic flow alteration and associated management actions.

Approach

All stream reaches in the State of California will be classified based on inherent physical properties and setting that are expected to influence flow patterns. All streams segments from the National Hydrography Dataset (NHD) for California will serve as the base layer for classification (ca. 150,000 segments). Each stream segment will be attributed with approximately 150 physical characteristics assigned at the drainage area scale. These characteristics include topography, geology, soil type, and long-term (1950-2000) average precipitation and other climatic attributes. Stream segments will also be attributed with geomorphic variables, such as valley confinement and estimated stream power. The
physical characteristics most influential to streamflows will be selected from the larger set based on examination of relevant literature and the application of first principles. Classification of segments will then be performed based on the selected subset of physical characteristics. Initial classifications will be reviewed to determine if they are consistent with general physical patterns that may affect stream structure and past efforts to classify streams in California. Apparent inconsistencies or anomalies in the initial classification will be addressed through iterative refinement of the classification model.

The technique of Bayesian mixture modeling (BMM) will be used to perform the classification. BMM has several advantages for hydrological classification (Webb et al. 2007, Kennard et al. 2010), most important being the way in which classes are created. There is no need to identify the number of classes a priori, and the BMM procedure does not create "hard" classifications; the probability of membership for each observation into each class is computed. This better reflects the natural world because there are many streams that may be transitional from one distinct type (e.g., snow melt perennial) to another (e.g., snow melt-winter rain perennial). BMM-based classification will be performed using a procedure developed by NASA (http://ti.arc.nasa.gov/tech/rse/synthesis-projects-applications/autoclass/autoclass-c/).

Products

- GIS data layer and geodatabase of all stream segments and their classification
- Brief memo or report summarizing the classification process and the results
  - Description of the classification systems, including the dominant variable that define class membership
  - Summary tables of distribution of streams by class in California
  - Discussion of the relationship of this classification to other systems currently in use to support water quality or hydromodification management.

Task 2: Determine Likelihood of Flow Alteration of California Streams Based on Anthropogenic Land Uses

Purpose

The purpose of the status classification is to provide an estimate of the likelihood that streamflows are modified/altered by anthropogenic activities for every stream segment in the state. At the state-wide, regional, and local scales such a classification provides a coarse tool with which to identify where stream health is potentially degraded by altered flows. The products of this task can be used to prioritize locations for more intensive investigation in subsequent tasks.

Approach
All stream segments in California will be divided into two categories, altered vs. unaltered, based on their monthly flow patterns. Daily flow patterns will be explored, but may not be emphasized due to the difficulty in modeling daily flows in subsequent tasks. Models that predict the flow status (i.e., reference vs. altered) of streams are best if developed using data from actual streamflow monitoring. There are ~700 USGS stream gages throughout California, most of which are influenced by a wide variety of land and water management activities. Expected monthly flows will be calculated for each segment that corresponds to a gage location using the procedure described by (Carlisle et al. in preparation) Actual monthly streamflow data from these gaging sites will be averaged over the ten year period 2000-2010, and then compared to expected natural monthly flows developed with existing models. The comparison of actual and expected monthly flows will allow for initial assignment of stream segments as either “reference” using criteria previously developed by USGS or “altered”. Streamflow departures from reference at altered sites will be examined as continuous variables across a gradient of human influence. With these departures as the dependent variable, models will be developed that predict the degree of flow alteration using watershed characteristics that are indicative of land and water management, such as land cover, reservoir storage, water withdrawal, etc. Predictor variables that are widely available and can be computed for all stream segments will be prioritized. The resulting statistical models will be applied to all stream segments throughout the state, thereby producing an estimate of the extent of flow alteration for every stream segment in California.

Products

- GIS data layer and geodatabase of all stream segments attributed with expected and actual monthly flows (where gages are available).
- GIS data layer and geodatabase of all stream segments attributed as either altered or unaltered based on model results.
- Brief memo or report summarizing the attribution process and the results
  - Description of the approach to determine flow status (altered vs. unaltered), including the dominant landscape variable that define class membership
  - Description of the thresholds used to determine flow status
  - Summary tables of distribution of streams in California by flow status

Task 3: Relate Location of Bioassessment Sites to Availability of Long-term Flow Data

Purpose

This task will provide the temporal and spatial relationship between bioassessment data and long-term flow gage data for the State of California. This relationship will be used in several of the subsequent tasks in the project to help relate changes in flow to biological condition.
Approach

An inventory of USGS streamflow gages will be mapped against an inventory of biomonitoring sites in California. The locations of these gages will be compared to the locations of bioassessment sites that have been sampled by State or regional biomonitoring programs over the past 10 years. Viable matches between streamflow gages and biomonitoring sites will meet the following criteria:

- Biomonitoring site must be located on the same stream as the USGS streamflow gage, but can be located either upstream or downstream
- Proximity of USGS streamflow gage to biomonitoring site limited by a maximum difference in watershed areas. The maximum difference will be chosen to balance the ability to maintain adequate sample size with fidelity of conditions to the gage record. This will be informed by checking relationships with regional flow regressions to assess whether the expected difference in magnitude between the gage and biomonitoring site is substantial
- No major tributary influence between USGS streamflow gage and biomonitoring site
- USGS streamflow gage record must overlap with date of sampling at biomonitoring site
- Minimize effect of intensive land use between USGS streamflow gage and biomonitoring site
- No intervening dams or diversions must be present

These criteria ensure spatial and temporal proximity of the USGS streamflow gage data to the biomonitoring data. Criteria will be assessed by mapping the gages and biomonitoring sites, and using a combination of tools such as Google Earth imagery, land cover/land use GIS layers, and USGS streamflow gage annual reports. A difference in watershed area analysis will be performed to find matches between USGS streamflow gages and biomonitoring sites that exhibit minimal change in watershed area, and at the same time provide a large enough sample size for robust statistical analysis. The difference in watershed areas will be related to appropriate USGS regional regression equations in order to assess the magnitude by which the change in area results in a change of predicted flow. If an intervening tributary does not result in a difference in watershed size greater than the maximum allowable difference, then the tributary is deemed not significant. Identification and quantification of intervening water diversion will be assessed by using a combination of USGS annual gage reports, USGS gage GIS data, and Google Earth for visual identification of diversion structures. Intensive intervening land use, as well as dams or diversions, would result in significantly different flow regimes experienced by the gage and biomonitoring site locations and could therefore cause us to eliminate some gages from use for development of models.

Products

- Map (and associated geodatabase) showing location of biomonitoring sites relative to USGS gage station
  - Year in which biomonitoring occurred
  - Period of record for gages
Task 4: Calculate Flow Metrics

Purpose

The purpose of this task is to calculate a range of flow metrics that may affect benthic community composition and abundances. For each stream type, there is a range of natural hydrologic variation that regulates characteristic ecological processes and habitat (Arthington, et al., 2006; Lytle & Poff, 2004), and that represents the baseline or reference condition against which biological responses to alteration can be assessed along a gradient of hydrologic alteration (Poff et al., 2011). Consequently a variety of flow metrics need to be evaluated for recommendation of flow criteria.

Approach

A series of ecologically relevant flow metrics will be calculated for all gaged stream segments in California. Konrad et al. (2008) identified that metrics of streamflow variation at daily to inter-annual scales were among the most common characteristics associated with limits on invertebrate assemblages. Example metrics that may be evaluated include time to return to baseflow (following a high-flow event), daily flow variation, monthly flow variation, high-flow duration, and minimum daily streamflow. A variety of flow statistics can be calculated using software packages such as the Indicators of Hydrologic Alteration (Richter et al., 1996), the Hydrologic Assessment Tool (HAT; Henriksen et al., 2006), or GeoTools (Bledsoe et al. 2007). These packages, along with traditional multivariate statistical approaches, will be explored to determine a subset of indices that may be incorporated into flow criteria. Results of the stream classification (Task 1) will also be used to inform the selection of relevant flow metrics. Flow metrics will be selected based on four criteria: 1) capacity to capture the range of natural hydrologic variability, 2) known ecological relevance and sensitivity to regional styles of flow alteration, 3) prediction accuracy (confidence) of models for a given metric, and 4) interpretability and utility in a management context. In selecting the candidate streamflow metrics, we will use a redundancy analysis to determine which variables are the most informative components of the flow regime (Olden and Poff, 2003). The goal is to produce a list of approximately 5-15 flow metrics that are most relevant for the subsequent analysis of flow-ecology relationships, described below.

The classification system developed under Task 1 will be used to compare flow metrics between stream types and to compare altered to unaltered streams. This allows the development of relationships between ecological metrics and flow alteration for an entire stream type based on data obtained from a limited set of rivers of that type within the region (Arthington, et al., 2006; Poff, et al., 2006). It will also provide insight into which metrics may the most sensitive to changes in condition associated with anthropogenic activities.

Products

• Streamflow metrics for each gaged stream segment in California
• List of priority flow metrics by stream type
• Brief memo with a summary of differences between key streamflow metrics at altered vs unaltered sites

Task 5: Develop Local and Intermediate Scale Models for Predicting Key Flow Metrics

Purpose

The purpose of this task is to develop ca. 20 calibrated rainfall-runoff models for a local study area (e.g. San Diego County) as well as intermediate complexity models (e.g. sub-regional regressions / random forests) that nest within statewide and regional models developed under Task 2. These models will allow the estimation of key flow metrics over multiple time scales. Changes in estimated flow metrics in response to land use or management actions can be used to support regulatory or planning decisions.

Approach

Mechanistic rainfall-runoff models will be developed and calibrated for a series of watersheds so that ecologically relevant flow metrics (determined under Task 4) can be calculated for bioassessment sites using model output. Watersheds will be selected to encompass a range of conditions based on the classification developed in Task 1 and on different land use patterns. Models will be parameterized through a variety of means. Calibrated mechanistic rainfall-runoff models will be used to represent the finest resolution for determining ecologically relevant flow metrics. Rainfall-runoff modeling can be considered the finest resolution due to the high number of watershed-specific physical parameters that rainfall-runoff modeling requires. Some of these physical parameters will be directly calculated from basin and climate data, some will be accurately estimated using GIS and historical records, and many other parameters will need to be estimated and adjusted through model calibration to existing streamflow gages. The produced rainfall-runoff models will be continuous in time, not event-based, so that each model will represent long-term flow conditions and not stream response to just one storm. A major objective of this project is to create long-term continuous models that include the entire range of benthic macroinvertebrate sampling dates; however, determinations of model accuracy will heavily emphasize shorter time intervals corresponding with previous macroinvertebrate sampling.

Rainfall-runoff modeling will first be attempted using the US Army Corps of Engineers’ HEC-HMS software. Parameters associated with the Simple Canopy, Simple Surface, Soil Moisture Accounting (Loss), Clark Unit Hydrograph (Transform), and Linear Reservoir (Baseflow) methods will be used initially. If these modeling Methods appear insufficient, other methods in HEC-HMS will be explored before trying a different rainfall-runoff modeling program, such as the USEPA/USGS Hydrologic Simulation Program-Fortran (HSPF) or the USEPA Storm Water Management Model (SWMM) software packages.
Finally, parameter optimization tools from within the rainfall-runoff modeling programs, and from external sources, will be examined as a potential means of improving parameter calibration and model accuracy. To the extent possible, we will coordinate and leverage existing modeling efforts ongoing in southern California. It is important to note that the final model approach will be based on a determination of the tools the desired indicators and output. The choice of indicators used will not be dictated by the model(s) selected.

In addition to the fine resolution rainfall-runoff models, intermediate complexity models will be developed that use less regionally-based physical data than the rainfall-runoff models, but include more than the statewide hydrologic analysis. These models may involve developing sub-regional regression relationships in order to generate flow metrics to describe benthic macroinvertebrate assemblage and predict effects of hydromodification. Another option for these intermediate complexity models involves creating Random Forest or other statistical models at the sub-regional scale. Sub-regional Random Forest models are created using only data from streams in the same sub-region. By using a Random Forest model created using only streams within the same sub-region, statistically produced flow metrics should theoretically be more representative of the region. Additionally, state-wide or sub-regional Random Forest models may be used to inform calibration of rain-fall runoff models in an effort to combine physical and empirical approaches.

**Task 5.1: Rainfall-Runoff Model Calibration and Testing**

**Approach**

Models will be calibrated through comparison of output to measured flow at USGS gage locations. Calibration of each gaged model will occur over a series of temporal increments. Initially, a short modeled time period (few months) will be used for calibration. The modeling time period will then be expanded to a medium length (1-2 years), before final expansion into a continuous model that accurately captures the entire range of macroinvertebrate sampling dates (15 years at most). This series of temporal increases for each gaged model will lend itself to better parameter estimation and calibration. Adjusting unknown model parameters to accurately replicate key gaged flow series hydrograph features (such as relative occurrence of flow peaks, baseflow duration, and total volume of flow), is easier for shorter durations, and increases in difficulty with model duration, due to increasing hydrograph complexity. Knowledge gained from adjusting the parameters to accurately model a few months will assist in adjusting the parameters to accurately model longer durations. It is extremely possible that one model hydrograph will not accurately capture all important aspects of the gage hydrograph (relative occurrence of flow peaks, baseflow duration, and total volume of flow). If this occurs, multiple models will be formulated for each site in an attempt to capture all important aspects of the gage hydrograph.

Sensitivity analyses will be performed on a diverse subset of models to systematically determine which parameters most affect the relative occurrence of flow peaks, baseflow duration/intermittency, and
total volume of flow. The parameters that most influence key components of the modeled flow series will be the focus of continued model calibration. Establishing relationships between watershed attributes and the parameters that are the most sensitive within a gaged model, as well as reasonable ranges of parameter inputs, provide a rational basis for parameter estimation at ungaged bioassessment sites. Although long-term climate change may affect the sensitivity (and performance) of the models, addressing these long term changes in model output is beyond the scope of this project.

Ungaged bioassessment sites will be matched to one or more stream gage sites using the approaches described under Tasks 1 and 2 (e.g. land use, climate, geology, flow intermittency). Depending on the quality of match, uncalculated and uncertain model parameters of the bioassessment basins will be extrapolated from the modeled gaged basins. Determining how greatly to adjust parameters will rely heavily on field data comparisons of stream gage sites and bioassessment sites, previous sensitivity analyses, and proximity of bioassessment site to the nearest modeled stream gage site. Differences between a bioassessment site and a gage site will be analyzed to quantify input parameter adjustments and generate time series of flow data at ungaged bioassessment sites. Additionally, models for bioassessment sites will be re-analyzed without changing input parameters from gaged basins. This will be done to examine the extent to which extrapolation of rainfall-runoff models to ungaged basins is feasible (in terms of model prediction accuracy) across the landscape gradients and stream types defined in Tasks 1 and 2.

Products

- Series of calibrated rainfall runoff models that represent a range of watershed types in southern California
  - Results of sensitivity analysis and model testing showing most critical model parameters
- GIS data layer (and associated database) of flow metrics calculated at various time scales for representative ungaged stream reaches

Task 6: Assess and Describe Prediction Accuracy of Different Tiers of Models Across Regional Gradients.

Purpose

The purpose of this task is to determine which scale of models (statewide, regional, or local) is most effective at discerning the effects of various natural and anthropogenic gradients on ecologically relevant flow metrics. This will support recommendations that balance model accuracy against cost and level of effort.

Approach
Models will be evaluated across several gradients identified by the project team and reviewed by the project Technical Advisory Committee. Due to the hydromodification management aspect of this project, land use and human influence will be essential gradients upon which to assess the prediction accuracy of the different tiers of models. For the land use gradient, the relative impacts of urban residential, rural residential, agriculture, commercial, and natural land uses will be considered. Additionally, parameters such as road density and percent imperviousness will be used to establish a gradient of human influence.

Another critical gradient upon which the accuracy of the different tiers of models will be assessed is flow intermittency. One major expected outcome of this project is to better understand how the complexity of Southern California’s abundance of ephemeral and intermittent streams can best be managed. Extended periods of very low or no flow are known to play critical roles in benthic macroinvertebrate assemblages (Miller et al. 2007, Poff & Zimmerman 2010), but are also difficult to model. A third gradient by which the prediction accuracy of the models will be compared is the overall climate, topography, and physical setting of each site. For this gradient, factors such as elevation changes, proximity to the coast, vegetation, and average temperature/expected rainfall will be used. Finally, the geology of each site is a critical gradient upon which to assess model accuracies. While it might be expected that geology closely correlates with climate and elevation, this gradient affects baseflows and flow intermittency, as well as the overall form and structure of the streams. In addition to channel sediment properties, this gradient will attempt to classify characteristics such as sinuosity, and stream type. Anastomosing streams or streams undergoing different types of erosion, such as incising or head cutting will be analyzed differently for prediction accuracy via this gradient.

Prediction accuracy of each of the aforementioned types of hydrologic models will be assessed by applying estimates of flow patterns at sites with streamflow gages. The generated time-series of flow from each model can then be compared to the gage time series for critical hydrograph features to determine prediction accuracy. Additionally, streamflow metrics critical to benthic macroinvertebrate assemblages will be calculated from each modeled time series and compared to the gage-generated data for prediction accuracy. An anticipated potential result of these comparisons is that one model might predict some features of the hydrograph very well, but others poorly. For this reason, model accuracy will be determined by analyzing a suite of individualized key hydrograph features and flow metrics. The study sites will be categorized based on their landscape position and land use characteristics to ultimately assess the prediction accuracy of each type of hydrologic modeling approach with respect to the most relevant flow indices within each category.

**Products**

- Results of analysis of scale effects of flow metrics
• Recommendation for the appropriate scale model to applied for various natural and anthropogenic gradient
• Memo with graphics that describe ranges of ecologically relevant flow metrics across various gradients

**Task 7: Relate Streamflow metrics to Changes in Land Use and Other Stressors**

**Purpose**
The purpose of this task is to determine how changes in land use (including impoundments and diversions) affect streamflow metrics. This information will support predictions of how changes in land use may affect flow and in turn biological integrity. Results of this task can also support decisions regarding stream management or restoration.

**Approach**
Ecologically relevant flow metrics will be compared to changes in land use based on the National Land Cover Database (NLCD). NLCD GIS coverages will be used to calculate percent agriculture and percent urban land cover of the watershed upstream of each USGS streamflow gage. Road density and percent imperviousness area are common surrogates used to quantify urbanization and will also be calculated for each of the gaged watersheds from GIS layers. If there are gaps in the land use gradients represented by the gaged watersheds, then streamflow metrics will be calculated for selected ungage d basins that have land use characteristics that fill identified gaps in the pool of gaged sites. These additional streamflow metrics may come from mechanistic rainfall-runoff models or from coarser scale regional models. The final set of watersheds with calculated streamflow and land use indices will then be used to perform hydrologic variation analysis for the study region. Streamflow metrics will be regressed against the four measures of land use (percent agriculture, percent urban land cover, percent impervious area, and road density) to find relationships between changes in land use and resultant changes to streamflow.

A Principal Components Analysis (PCA) will be employed to examine dominant patterns of intercorrelation among the suite of hydrologic indices and land use variables, and to identify subsets of indices that describe the major sources of variation while minimizing redundancy (i.e. multicollinearity). In this step, the PCA will be conducted using the correlation matrix rather than the covariance matrix because we are interested in examining relationships among the hydrologic indices. Using the correlation matrix also ensures that all indices contribute equally to the PCA and that these contributions are scale-independent.

**Products**
• Memo summarizing the relationship between changes in land use and changes in streamflow metrics
  o Summarize most sensitive streamflow metrics
  o Summarize metrics with the greatest information content for discerning among regional flow patterns
  o Summarize model performance
• GIS data layer of flow metrics for all stream reaches evaluated

**Task 8: Develop Hydraulic Metrics for Assessment of Habitat Effect on Biological Communities**

**Purpose**

The purpose of this task is to use physical habitat data to translate discharge metrics from the USGS gages matched to biomonitoring sites in Task 3 into hydraulic metrics that reflect condition of the channel substrate, boundary material, and form. These hydraulic metrics will be used in a subsequent task as a way to relate flow to biological condition (via effects on habitat).

**Approach**

Hydraulic metrics will be calculated in order to describe the frequency with which the bed is mobilized at the bioassessment sites given existing flow data. This information will be used to help support development of flow ecology relationships (see Task 9). The time series of discharges will be converted to a time series of hydraulic parameters. The time series of hydraulic parameters will be input into software packages such as Indicators of Hydrologic Alteration (IHA), Hydrologic Assessment Tool (HAT), and GeoTools to produce hydraulic metrics. Though these software packages were originally intended to take in a time series of discharges, any type of time series can actually be input. The interpretation of the output will depend on the type of time series entered. For example, if a discharge time series is input the programs may calculate a metric such as time mean annual discharge. If a time series of dimensionless shear stresses is input instead, the output will then just be mean annual dimensionless shear stress.

Hydraulic metrics that will be calculated at biomonitoring sites in the study region include dimensionless shear stress and dimensionless specific stream power. Dimensionless shear stress is calculated as follows:

\[
\tau_* = \frac{\tau}{(\gamma_s - \gamma)d_{50}} = \frac{RS}{1.65d_{50}} \approx \frac{hS}{1.65d_{50}}
\]

where,
\[ \tau^* = \text{dimensionless shear stress}; \]
\[ \tau = \text{shear stress}; \]
\[ \gamma_s = \text{specific weight of sediment}; \]
\[ \gamma = \text{specific weight of the water}; \]
\[ d_{50} = \text{median diameter of bed material}; \]
\[ R = \text{hydraulic radius} \]
\[ h = \text{depth of flow}; \]
\[ S = \text{bed slope}. \]

Depth of flow \( (h) \) is calculated for each discharge in the time series of discharges using channel geometric data from each site as described below. The Manning equation below is used to convert discharge to depth of flow, which is then used in the dimensionless shear stress equation above.

\[
Q = \frac{\phi}{n} A R^{\frac{2}{3}} S^{\frac{1}{2}} \approx \frac{\phi}{n} A h^{\frac{2}{3}} S^{\frac{1}{2}}
\]

where,
\[
Q = \text{discharge}; \\
A = \text{cross sectional area}; \\
\phi = \text{constant (1.49 English, 1 International System of Units (SI))}; \\
n = \text{Manning roughness coefficient}; \\
R = \text{hydraulic radius}; \\
h = \text{depth of flow}; \]
\[ S = \text{bed slope}. \]

Dimensionless specific stream power will also be calculated as follows for each biomonitoring site:

\[
\omega^* = \frac{\omega}{\rho (1.65gd_{50})^3} = \frac{\rho g Q S}{b} \left( \frac{1}{\rho (1.65gd_{50})^3} \right)
\]

where,
\[
\omega^* = \text{dimensionless specific stream power}; \\
\omega = \text{specific stream power}; \\
\rho = \text{density of the water}; \\
g = \text{acceleration due to gravity}; \\
d_{50} = \text{median diameter of bed material}; \\
b = \text{width of channel}; \\
S = \text{bed slope}. \]

Calculating hydraulic parameters for biomonitoring sites requires additional information on physical characteristics of the channel and substrate. These data will come either from previously collected
physical habitat (PHAB) data or from new data on channel geometry collected as part of this study. The PHAB metrics of interest for converting discharge to dimensionless shear stress and dimensionless unit stream power are average channel slope, $d_{50}$ of the substrate, and bankfull width. In order to use the available PHAB data for calculating dimensionless shear stress, a rectangular cross section, with width equal to the reported bankfull width, must be assumed. A Manning n roughness value must also be estimated from available photographs.

PHAB data are routinely collected in conjunction with macroinvertebrate sampling performed by the State of California. Inventory of available PHAB data will be performed for biomonitoring locations. Particular emphasis will be given to assessing the availability of select PHAB metrics that characterize the channel cross section, slope, and substrate. Together with photographic records, these select PHAB metrics will be used to convert discharge metrics at biomonitoring sites to hydraulic metrics where these metrics are available. The efficacy of using PHAB data will be evaluated by comparing hydraulic metrics calculated using PHAB data to hydraulic metrics calculated from additional field data that will be collected for the express purpose of developing these hydraulic metrics at a subset of sites; channel cross section, substrate size, and channel slope (see Task 8.1).

**Task 8.1: Field Measurement of Hydraulic Parameters**

**Approach**

Field data will be collected at a subset of biomonitoring sites to augment existing PHAB data and assess the relative accuracy of hydraulic metrics based on synoptic versus more detailed channel surveys. The additional field data will allow some biomonitoring sites to be analyzed which do not have the required PHAB data available for converting discharge to hydraulic metrics. A representative cross section (or in some cases multiple cross-sections) will be selected for detailed survey at each selected biomonitoring site. A total station will be set up near the cross section in a location that minimizes line of sight issues. Across the cross section, points will be located at small enough intervals to capture the cross section shape, as accurately as possible, with a focus on recording topography taking shots where there exists a break in slope. The total station will also be used to measure the longitudinal profile of each biomonitoring reach by recording measurements along the channel lowpoint, or thalweg.

Substrate at each biomonitoring site will be quantified. If the substrate is uniform sand, this will be recorded on the field survey sheets. The $d_{50}$ of sand will not be quantified by sieving because sand is usually mobile at even very low levels of flow, and the hydraulic metrics are being used to describe conditions when the bed is mobile. If the substrate contains a mix of sand, and gravel or cobbles, size of the substrate will be quantified by performance of a pebble count of at least 100 particles. A sampling grid will be placed in the stream at random and 100 particles measured across the entire cross section from bankfull to bankfull. The sampling grid is a metal frame that is strung with string to create nine intersections. At each string intersection, the first particle touched will be measured using a gravelometer. Anything less than 2 mm in size will be recorded as “fines”. Each particle will be
measured along the intermediate axis. The measured particle will then be used to determine a median substrate size \( (d_{50}) \) for the cross section.

At each site, GPS coordinates will be recorded and photographs will be taken to help with estimation of Manning’s \( n \) values. At a minimum, photos will be taken at the cross section looking upstream, downstream, toward left bank, and toward right bank. Photos will also be taken of any structures expected to have an impact on the streamflow.

**Products**

- Summary of hydraulic parameters for measured stream reaches, including ranges of conditions by stream type
- Relationships between flow and hydraulic parameters
- Proposed hydraulic “metrics” for evaluating biological effects of hydromodification

**Task 9: Analyze Relationship between Flow Metrics and Biological Condition**

**Purpose**

The purpose of this task is to determine which flow and hydraulic metrics (developed during previous tasks) are most closely related to bioassessment metrics. This task will also result in a set of models based on the most promising flow-ecology relationships. These relationships will form the foundation for future development of flow criteria.

**Approach**

Flow-ecology relationships will be developed using the statewide data sets by utilizing the previously identified streamflow and hydraulic metrics and developing models to relate them to taxonomic and functional based biological metrics. The analysis will start with simple linear regression, and progress to quantile regression, multivariate statistical methods, and artificial neural networks as necessary to improve predictive power and selection of the most parsimonious model of the flow-ecology relationships.

Flow-ecology relationships will be developed using biological metrics that describe the taxonomic structure as well as the functional composition of biomonitoring locations. Taxonomic-based metrics such as richness, % Ephemeroptera, Plecoptera, and Tricoptera (EPT) taxa, and % Chironomids are readily calculated from available biological data. This study however will also quantify the biological integrity of biomonitoring sites by calculating functional trait based metrics. In order to calculate these functional trait based metrics, an existing traits database (Poff et al. 2006) must be enhanced to include species specific to California streams, which it is currently lacking. This effort will be led by collaborators at CSU.
The exploration of relations between flow (discharge) and hydraulic metrics and biological condition will begin by developing a series of plausible and testable hypotheses. The tentative hypotheses will be identified based on expert knowledge of the region (within the TAC and science team) and understanding of the rapidly growing hydro-ecological literature (e.g., see http://conserveonline.org/workspaces/eloha/documents/flow-ecology-relationships-0, http://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/Methods andTools/Pages/environmental-flows-metho.aspx). An iterative process will be used to build statistical models ranging from regression to more sophisticated modeling tools such as random forests and boosted regression trees. Advanced nonlinear modeling techniques are required because functional relations between biological responses and various kinds of flow alteration can take many forms (Arthington et al. 2006), from monotonic to unimodal to polynomial to thresholds. The results of this analysis will be used to recommend a set of biological metrics that may be most useful in the application of flow-ecology relationships. These metrics could include community based metrics, diversity and richness based metrics, functional metrics, or trait-based metrics. We will attempt to account for the role of hydrologic alteration relative to other potential stressors (e.g. chemical stressors) through the modeling efforts and focus on metrics that are most tightly related to changes in hydrologic or hydraulic conditions. This may be limited by the availability of data on other stressors and by the ability of the models to separate out the contribution of the related factors of hydrologic vs. chemical stress.

Ultimately, these analyses will produce a set of recommended statistical models for different stream types that can be used to relate flow and/or hydraulic metrics to biological metrics. The resulting models can be the foundation for developing flow criteria. In addition to providing a foundation for understanding how biota are affected by hydromodification, the result of this modeling exercise will allow identification of critical information gaps and research needs to be addressed in future work. The models will focus on the relationship with benthic macroinvertebrates, but the general relationships could be explored for other biological endpoints (e.g. fish) through subsequent efforts.

**Task 9.1: Collection of Supplemental Bioassessment Data**

**Approach**

Analysis of flow-ecology relationships requires a robust set of locations that have both flow and bioassessment data. Sites with both data types should span the range of natural and anthropogenic gradients (analyzed during earlier tasks). Results from Task 3 will be analyzed to determine where data gaps exist. New biological and environmental data will be collected at approximately 40 sites. New sampling sites will be selected from stream reaches with flow records from active stream gages, but where no recent bioassessment data is available. Priority will be given to sites representative of minimally altered flow regimes (based on prior analysis) and/or where portions of natural gradients are not well represented by the available data. Standard bioassessment methods will be used for monitoring of benthic macroinvertebrates. Physical habitat data will be collected as described in Task 8 and include cross-section and longitudinal profiles. This will allow calculation of hydraulic metrics in addition to flow metrics.
Products

- Summary of bioassessment data from new sites and description of how the new data helps to fill existing data gaps
- Summary and description of key flow and hydraulic metrics that are most closely related to changes in biological condition for each major stream class
- Summary and description of the bioassessment metrics most responsive to changes in flow or hydraulic parameters
- Memo describing flow-ecology and hydraulic-ecology relationships with the most promise for use in setting regulatory, monitoring, or performance objectives (including recommended models for establishing such objectives)

Task 10: Evaluate Performance of Various Scoring Tools at Predicting Flow-ecology Relationships

Purpose

The purpose of this task is to test the performance of models produced at different scales and resolutions with regard to their ability to differentiate reference from non-reference sites based on flow-ecology relationships. The results of this analysis can be used to develop a set of scoring tools that could be used in the application of flow criteria.

Approach

Models will be evaluated to determine their ability to differentiate reference vs. non-reference (i.e. altered vs. unaltered) conditions across a variety of stream types. Performance of statewide statistical models will be compared to the intermediate and local scale models developed during earlier tasks. The statistical approaches described above will be used to perform correlative analysis of aquatic invertebrate composition (taxonomic and trait-based) and hydrologic metrics provided by three different types / resolutions of hydrologic descriptors. First, relationships between stream biological data and regional hydroclimatic data, USGS regional regression relationships, and regional analysis of reference gages will be examined. Second, intermediate complexity hydrologic models that provide relatively accurate estimates of streamflow characteristics across gradients of land use will be evaluated. These models will include Random Forest models that account for flow intermittency and the effects of land use. Finally, rainfall-runoff models (HEC-HMS) as described above that provide streamflows with sub-daily resolution and greater spatial detail on the effects of watershed soils, land use, etc. will be tested. These three types of hydrologic foundations will be used to generate candidate flow and hydraulic metrics that will serve as inputs for statistical modeling. The variance in biological data explained (e.g., $R^2$, % correctly classified) by each type of hydrologic foundation will be examined to identify the relative increase in prediction accuracy that results from increasing hydrologic resolution and modeling effort in different geologic/climatic settings. The results of this analysis will be used to produce a set of recommendations for scoring tools under a variety of situations. The tools may vary
depending on availability of stream gage data vs. need to rely on modeled data or on the predictive power of the various tools for specific stream types.

Products

- Memo describing the results of the analysis of model performance, including specific recommendations resulting from that analysis
- Recommendations for specific scoring tools based on stream type, availability of data or other determining factors

Task 11: Demonstrate application of Flow-ecology (ELOHA) framework to develop flow criteria in a pilot watershed(s).

Purpose

The purpose of this task is to demonstrate how flow-ecology and/or hydraulic-ecology relationships can be applied in a regulatory or management context. This will be accomplished by demonstrating application of the models and scoring tools developed during earlier tasks in one or more pilot watersheds in the southern California region.

Approach

One or more watersheds will be selected to demonstrate the application of the flow-ecology (ELOHA) framework for establishing flow criteria. The goal of this task is to demonstrate how flow-ecology and/or hydraulic-ecology relationships can be applied in a regulatory or management context. Therefore, the specific demonstration area selected will be a location where an existing NPDES permit or management plan exists that can be used for the pilot application. Criteria for selection of the demonstration watershed(s) will include:

- Opportunity to implement tools in a variety of stream types
- Availability of past data/information
- Willing participants
- Coverage of data layers for hydrologic modeling
- Areas where flow changes are key biological drivers related to management decisions
- Areas likely to be subject to future changes

A hydrologic model will be developed for the target area and will be used to predict changes in the priority flow metrics (from earlier tasks) under future land use conditions. The results of the hydrologic modeling will serve as input into the flow-ecology models, which will be used to predict changes in bioassessment indices under the future development scenarios. A range of management actions will be identified and evaluated in coordination with the project TAC and the local stakeholders in the demonstration area. The pilot project will be used to demonstrate the following:
1. Verify classification system
2. Demonstrate assessment of stream segments based on flow & geomorphology metrics
   a. Based on gages, where they occur
   b. Based on models where there are no gages
   c. Produce descriptive statistics of flow metrics in pilot watershed(s)
3. Apply predictive modeling of changes in flow-metrics
4. Apply predictive modeling of changes in hydraulic metrics
5. Apply predictive modeling of changes in biology (bio-effects tools)
   a. Based on land use changes (expected future scenarios)
   b. Based on proposed management actions
6. Develop decision support tools that demonstrate how tools can be used to affect criteria or management actions (in coordination with local stakeholders)
7. Summarize lessons learned and transferability to other areas of the State
8. Recommend next steps for future application
   a. Summary of data and information needs

Evaluation of the effect of management actions will be used to demonstrate how the flow-ecology relationships can be used to support development of criteria, objectives, or monitoring requirements. To the extent possible, results will be provided in the context of individual regulatory or management programs, such as Section 401, NPDES, etc. Results will also be related to other ongoing flow-ecology efforts, such as those being conducted in the San Joaquin/Sacramento River area.

**Products**

- Summary of the performance of various models in the pilot watershed(s)
- Summary of sensitivity of the various biological metrics at differentiating effects of land use changes and management actions.
- Results of the case study(ies) with recommendation regarding application of the flow-ecology framework and recommendations for future actions.

**Schedule and Deliverables**

<table>
<thead>
<tr>
<th>TASK</th>
<th>GRANT TASK</th>
<th>SCALE</th>
<th>COMPLETION DATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Classify Streams based on Natural Hydroclimatic and Physical Characteristics</td>
<td>3.1, 3.4</td>
<td>statewide</td>
<td>June 2014</td>
</tr>
<tr>
<td>2 Determine Flow Status of California Streams Based on Anthropogenic Land Uses</td>
<td>3.1, 3.4</td>
<td>statewide</td>
<td>June 2014</td>
</tr>
<tr>
<td>3 Relate Location of Bioassessment Sites to Availability of Long-term Flow Data</td>
<td>3.3</td>
<td>statewide</td>
<td>June 2014</td>
</tr>
<tr>
<td>4 Calculate Flow Metrics</td>
<td>3.2</td>
<td>statewide</td>
<td>Aug. 2014</td>
</tr>
</tbody>
</table>
5 Develop Local and Intermediate Scale Models for Predicting Key Flow Metrics 3.2 S. CA June 2015
6 Assess and Describe Prediction Accuracy of Different Tiers of Models Across Regional Gradients. 3.2 statewide & S. CA Aug. 2015
7 Relate Streamflow Metrics to Changes in Land Use and Other Stressors 4.1, 4.2 S. CA Aug. 2015
8 Develop Hydraulic Metrics for Assessment of Habitat Effect on Biological Communities 4.2 S. CA June 2015
9 Analyze Relationship between Flow Metrics and Biological Condition 5.1 S. CA Jan. 2016
10 Evaluate Performance of Various Scoring Tools at Predicting Flow-ecology Relationships 5.1 S. CA March 2016

The deliverables will include GIS data layers, maps, and the results of statistical analysis. The final results of this work will be presented in one or more technical reports or journal articles. In many cases products from multiple tasks may be combined into overall summary or synthesis reports or papers.
Literature Cited


