Appendix G. An approach to refine ecological flow criteria through the development of distributed hydraulic response relationships

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Background

In some cases, reference flow criteria may be deemed inadequate for addressing ecological management goals. For instance, greater specificity may be desired in determining whether the reference flow criteria will sustain key ecological processes of interest. In such cases, ecological response relationships are needed to refine ecological flow criteria, as described in CEFF Section B. Here, we describe one possible approach for refining ecological flow criteria through the development of distributed hydraulic response relationships. **Hydraulic response relationships**[1] quantify changes in the distribution of depth and velocity conditions under different flows and link flow criteria to ecological outcomes that depend on hydraulic habitat conditions. The term **distributed** indicates that these relationships can be generated at numerous locations of interest (LOIs) across a geographic region. Analogous approaches could be developed for stream temperature or other mediating factors in order to refine flow criteria, but have not been considered here.

In the following sections, we (I) describe how hydraulic response relationships can be used to assess specific ecological outcomes, (II) introduce a method to develop distributed hydraulic response relationships for a geographic region of interest, and (III) provide an example application of this approach to a watershed in northern coastal California in the context of CEFF.

In the example application, we describe a management setting in which the dry-season base flow reference ecological flow criteria requires greater specificity with respect to native salmonid habitat needs. This is due to likely altered channel geomorphology and reduced riparian vegetation and increased stream heating, both of which may affect the ability of reference flow criteria to serve their natural functions. Hydraulic response relationships generated by the approach described in this appendix are used to relate dry-season baseflow magnitude to juvenile steelhead rearing conditions at LOIs across the watershed (Step 6, Figure 1). These flow-habitat relationships are then used to define dry-season baseflow flow criteria for different water year types (Step 7, Figure 1). Finally, the new flow criteria are integrated with the other reference flow criteria (from CEFF Section A) to generate ecological flow recommendations for LOIs across the watershed (Section B, Figure 1).

[1] ***Hydraulic response relationship***: Any quantitative relationship between streamflow and hydraulic conditions related to depth or velocity.

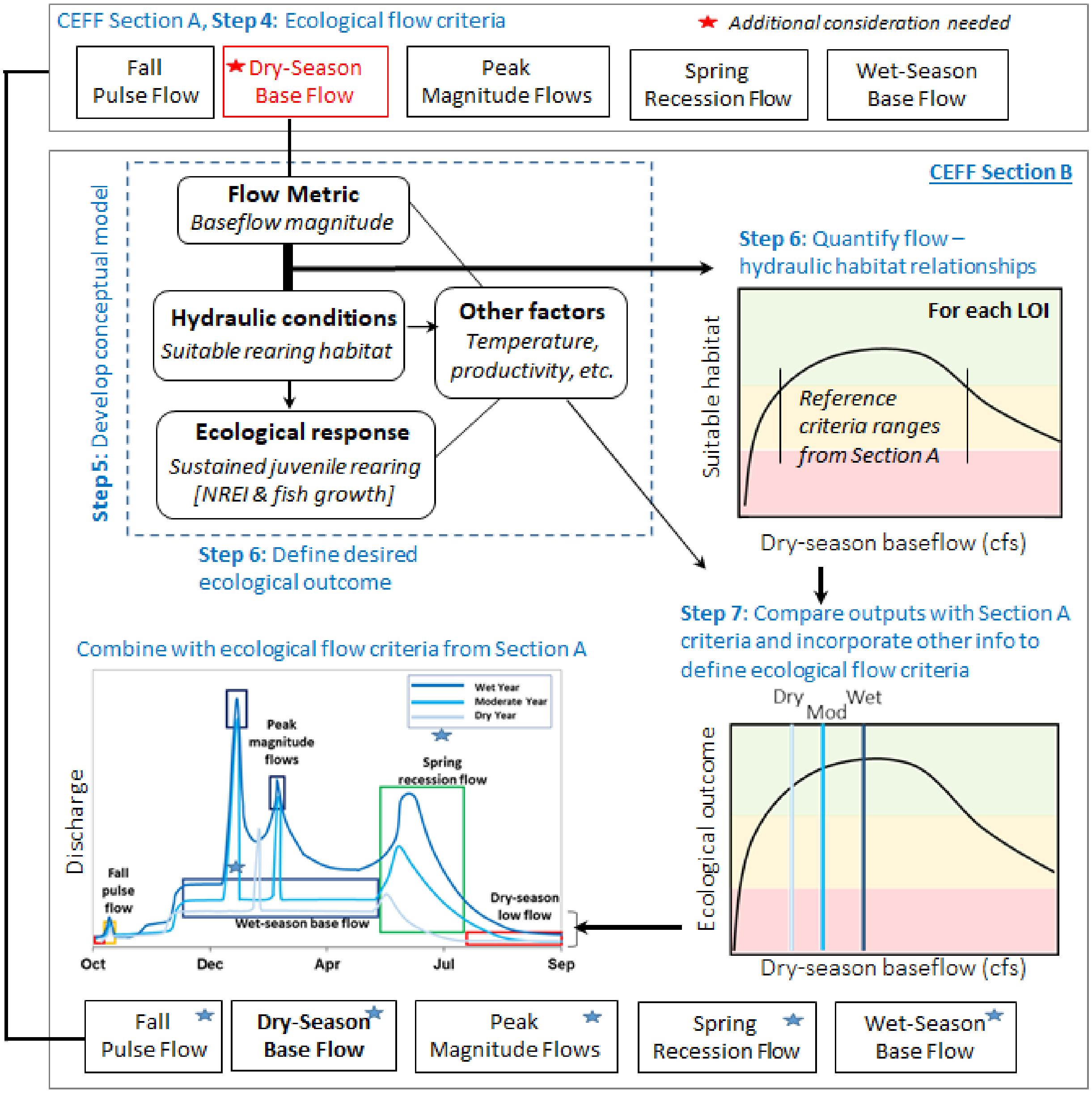

Figure 1. Example process for defining ecological flow criteria in CEFF Section B for flow components that require additional consideration. This appendix describes an approach for quantifying the relationship between flow metrics (i.e. dry-season baseflow magnitude) and hydraulic conditions at multiple LOIs to facilitate development of flow - ecology relationships (step 6) and ecological flow criteria in step 7. Similar approaches could be developed for stream temperature or other mediating factors identified in the conceptual model in order to refine ecological flow criteria for one or more functional flow components.

I. Introduction

Many native species and life stages in California depend on specific hydraulic habitat conditions at certain times and locations across a river network. For example, salmonids require specific ranges of water velocities for spawning and sufficient depth for upstream passage. Rearing juvenile salmonids also exhibit preferences for hydraulic habitat, defined by specific ranges of velocity and depth within streams. Functional flows are expected to broadly support beneficial hydraulic habitat conditions. However, in some situations, such as where specific desired ecological outcomes cannot be met by reference-based functional flows or where additional information is needed to balance ecological outcomes with human needs, users may want to more directly link streamflow to ecological outcomes via hydraulic habitat conditions. **Hydraulic response relationships**[2] quantify changes in the distribution of depth and velocity conditions under different flows and offer a means to link streamflow to ecological outcomes that rely on hydraulic habitat conditions.

Hydraulic response relationships can be linked to habitat preference or tolerance information in numerous ways to generate **ecological response relationships**[3]. These include summarizing flow-dependent hydraulic conditions into a single value representing expected habitat suitability, binary measures such as 'sufficient or insufficient flow for fish passage' or 'floodplain accessed or not accessed,' or more complex measures of spatial patterning such as habitat complexity (Gostner et al. 2013) or flow connectivity related to fish stranding and redd dewatering (Larrieu et al. 2019). Intensive site-specific field surveying and modeling efforts are well established and can provide detailed hydraulic and associated ecological response relationships. However, given the number of locations where this information is needed relative to available resources and time limitations, an approach is needed to generate and extrapolate hydraulic response relationships from resource intensive field studies to other locations of interest (LOIs) throughout a watershed where no site-specific information is available.

Numerous techniques are available to generate hydraulic-response relationships (though often using different terms) that simulate hydraulic conditions occurring under a range of flow at a particular location. Variations on the Instream Flow Incremental Methodology and its physical habitat component PHABSIM are very common, relying on intensive site-specific field data collection including measures of channel topography, velocities, depths, and substrate. Variability in depth, velocity, and shear stress can be described in terms of flow-dependent probability distributions based on observations or hydraulic model results. <u>However, given time and financial constraints, this process is generally limited to a few cross-sections or reaches of interest.</u> This limitation has prompted development of several procedures to extrapolate key information for understanding habitat response to changes in flow to unsurveyed reaches with similar geomorphic characteristics (Saraeva and Hardy 2009).

An underlying assumption of these extrapolation techniques is that stream networks within a watershed can be organized into groups of stream reaches exhibiting similar morphological attributes. Furthermore, a linkage is assumed to exist between site-specific field-based geomorphic and hydraulic attributes and broader scale landscape attributes such as drainage area, confinement, slope, geology, etc. This assumed linkage has promoted the development of extrapolation techniques that extend detailed geomorphic or hydraulic information to other similar reaches as identified based on readily available landscape attributes. Classification of channel reach geomorphic settings serves as a method to organize heterogeneous geomorphic and hydraulic

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[2] ***Hydraulic response relationship***: Any quantitative relationship between streamflow and hydraulic conditions related to depth or velocity.

[3] ***Ecological response relationship***: Any quantitative relationship between streamflow and an ecological outcome of interest.

conditions across entire watersheds based on dominant landscape controls. The resulting **channel types**[4] can be used to extrapolate resource intensive information collected at a single site, like hydraulic response relationships, to other locations with similar settings (Appendix F - Geomorphic Classification of California).

Here, we propose an approach to develop hydraulic response relationships for distinct channel types and extrapolate these relationships throughout a watershed using spatially distributed geomorphic classifications and targeted hydraulic modeling. The approach assumes that a given channel type will exhibit relatively consistent hydraulic response relationships throughout a watershed as long as discharge and hydraulic variables are described relative to bankfull conditions to account for established increases in channel dimensions downstream (Leopold and Maddock, 1953).

This approach improves on past studies in several ways. First, it utilizes robust statistical geomorphic classification and prediction techniques to classify regional stream networks into distinct channel types at the 200-m segment scale. Further, detailed topographic information and 2D hydraulic models can be used to retain biologically significant information related to spatial patterning of depth and velocity conditions. Finally, the approach is modular, providing the user with flexibility in the input terrains and rating curves based on data and resource availability, including readily available terrains for key channel types, user-friendly modeling tools to synthesize terrain at un-surveyed locations and scales, and detailed user-surveyed terrains.

The appendix describes an approach to stratify reaches in a watershed into groups of similar geomorphic settings based on landscape attributes, and to use these classifications to extrapolate hydraulic response relationships obtained at a subset of locations to other locations of interest in a watershed. The proposed approach is broadly applicable to different regions, flow regimes, geomorphic settings, and ecological management goals. The resulting hydraulic response relationships facilitate development of ecological flow regimes at numerous LOIs in a watershed with limited resources. Though outside the scope of this study, these hydraulic response relationships can also be linked with habitat preference or tolerance information or used as inputs to bioenergetics models to generate ecological response relationships as part of CEFF. The CEFF guidance document provides more detail on how to develop conceptual models (Section B, Step 5), quantify flow-ecology relationships (Step 6) and define ecological flow criteria for flow components requiring additional consideration after Section A (Step 7). Section C provides an overview of how the resulting flow criteria and flow-ecology relationships may be used to facilitate tradeoff assessment and development of environmental flow recommendations. *Appendix L* works through a more detailed example of this process for flow - hydraulics - ecology relationships.

[4] ***Channel type***: a statistically distinct group of stream reaches that exhibit similar channel attributes (e.g. bankfull width and depth, slope, etc.), topographic variability attributes (e.g. coefficient of variation of bankfull depth, etc.), sediment composition (e.g. d50 and d84) and landscape setting (e.g. valley confined, partly confined or unconfined) that can be verified in the field (Byrne et al. 2020)

When should I use these methods and tools?

Four conditions should be met for this method to be considered appropriate:

- The user identifies *several locations of interest* (LOIs) in **Section A, Step 1**.
- The user identifies that there is a need to *increase the specificity of ecological response relationships* for specific functional flow components to inform tradeoff analysis at these LOIs in **Section A, Step 3**.
- The conceptual model developed to refine reference flow criteria for desired ecological outcomes indicates that *geomorphology and/or hydraulics are important mediating factors* influencing these outcomes in **Section B, Step 5**.
- The relationship between hydraulics and ecological outcomes are well defined (or can be defined through additional studies) in the geographic region

II. Methods

The user can follow the steps below to generate hydraulic response relationships for LOIs. These hydraulic response relationships can then be combined with species or life-stage habitat preference/tolerance information or probability of species occurrence to assist in the development of refined ecological flow criteria (blue boxes, Figure 2). Key steps are to (a) develop or obtain a geomorphic classification for the geographic region, (b) select representative stream reaches in each classified channel type, (c) obtain high-resolution channel terrain of representative reaches, (d) run hydraulic models of each reach over a range of relevant discharges, and (e) generate hydraulic response relationships for all LOIs in the region (Figure 2). The following sections describe each of these steps, followed by an application of this approach in the South Fork Eel River watershed.

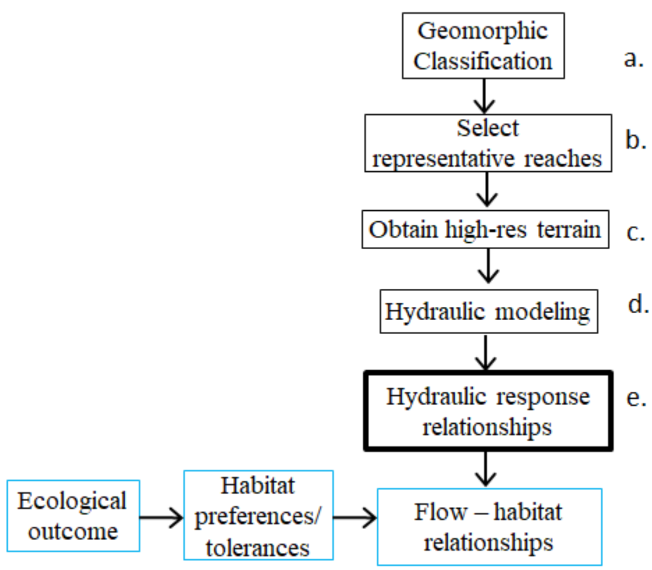

Figure 2. Main steps used to develop hydraulic response relationships for LOIs throughout a geographic region of interest. Geomorphic classifications have already been developed for many regions in California (Appendix J). The resulting hydraulic response relationships can be combined with the steps in blue boxes (from CEFF Steps 6-7) to generate ecological response relationships (CEFF Step 8-10) as part of CEFF.

(a) Geomorphic classification

Reach-scale geomorphic classifications serve as a method to organize complex channel networks with heterogeneous geomorphic and hydraulic conditions. Geomorphic classifications can be used to prioritize key flow metrics expected to be most significant in different geomorphic settings, stratify ecological response relationships, or extrapolate resource intensive information collected at a single site to other locations with similar settings, the last of which is described here (see Appendix F for more details). Numerous geomorphic classifications have been developed (Brierley and Fryirs, 2000; Church, 1992; Kasprak et al. 2016; Knighton, 1999; Buffington and Montgomery, 2013; Rosgen, 1994), with the most common being Rosgen, Montgomery and Buffington, and River Styles (Breirley and Fryirs 2000). While these classifications all have different merits and limitations, most are either not tailored to the particular conditions and context of the geographic region of interest (e.g., Rosgen, Montgomery and Buffington) or require substantial expert interpretation and field surveying (e.g., River Styles). For example, the Rosgen approach places sites into pre-defined channel types based on field-collected geomorphic attributes (e.g., slope, entrenchment ratio, width-to-depth ratio, sinuosity, and median grain size), which is useful in its simplicity but limited in that it assumes that any new field site will fit within one of the existing classes and leaves no opportunity to identify new patterns or channel types.

When possible, geomorphic classifications should be applicable in any region and support development of channel types that are physically interpretable, correspond with other established classifications, and incorporate regionally specific information to tailor the channel types to the specific physical basin and climate conditions and dominant geomorphic processes that may not be captured in more narrowly defined or broad classifications (Byrne et al. 2020).

To accomplish these aims, **geomorphic classifications were recently developed for nine major regions in California** (Figure 3) using a targeted field data driven, bottom-up statistical classification approach (Byrne et al 2020). This effort resulted in statistically distinct, interpretable and field-verifiable channel types for each region including channel types similar to those in existing classifications as well as less common channel types representing unique characteristics of the regions (Figure 4a). A robust machine learning algorithm was then used to predict the channel types (and associated uncertainty) of each 200-m stream segment in the regional stream networks based on readily available but coarse geospatial data related to landscape attributes (Figure 4b, Guillon et al. 2020). Appendix J provides an overview of these efforts, including data needs, methods, and key results related to the identified channel types and classified stream networks.

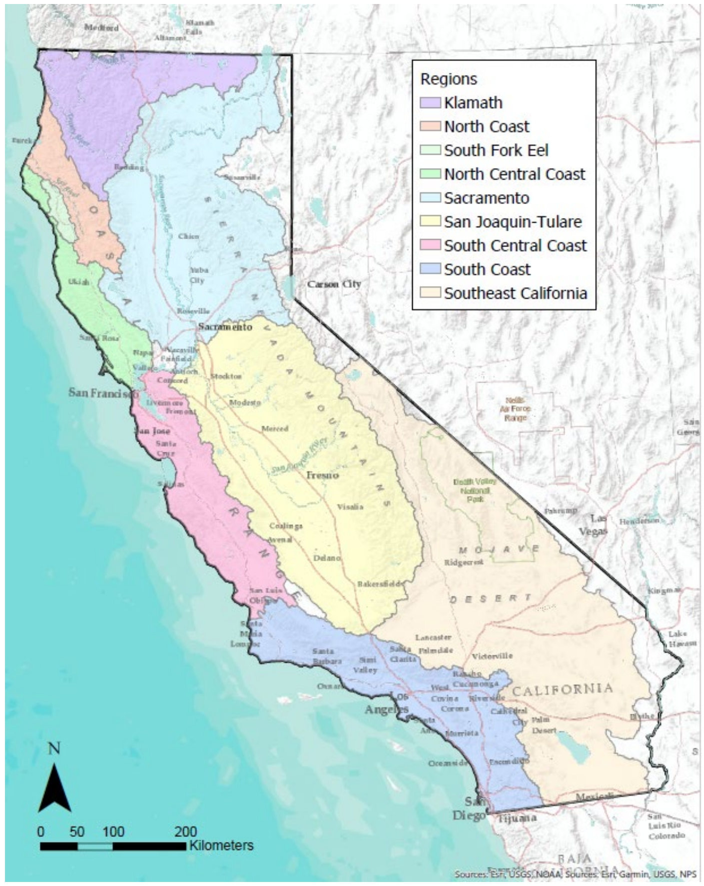

Figure 3. Map of geographic regions for which geomorphic classification have been developed.

A user may obtain an existing geomorphic classification for their region of interest, including but not limited to the nine regional classifications described above that will be made publicly available December 2020. Alternatively, a user may develop their own geomorphic classification that distinguishes reach-scale geomorphic settings expected to support distinct hydraulic responses at scales relevant to ecological outcomes of interest.

OUTCOME OF THIS STEP: A reach-scale geomorphic classification for the geographic region, consisting of a list of identified channel types and a map of their predicted spatial distribution across the stream network. Existing geomorphic classifications can be obtained for key regions of California, or the user can develop their own.

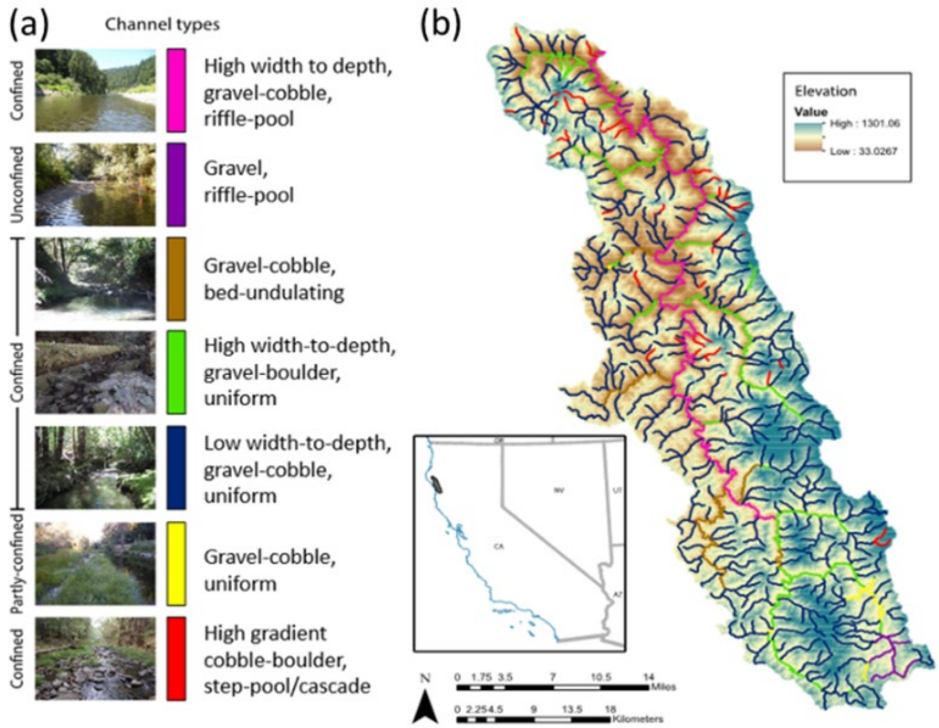

Figure 4. Geomorphic classification for the South Fork Eel River watershed: (a) distinct channel types identified from statistical analysis of field data and (b) watershed map of predicted channel types (see Appendix G for details).

(b) Select representative reaches

One or more representative reaches in each channel type should be selected for development of hydraulic response relationships that will then be extended to other reaches in the same channel type. This approach assumes that a given channel type will exhibit relatively consistent hydraulic response relationships throughout a stream network relative to bankfull conditions. If further discretization of geomorphic settings is desired, channel types can be binned by contributing area and representative reaches then selected for each sub-type. Using or developing a geomorphic classification expected to capture biologically relevant differences in geomorphic processes and hydraulic response relationships throughout the network should reduce the need for further discretization in this step. From all the stream segments classified as belonging to a single channel type (or channel type bin), representative reaches should be selected based on representation of median geomorphic attributes for that channel type, as well as accessibility if field-surveying is needed to obtain channel terrain (see step c). These representative reaches will be used for subsequent terrain development (step c) and hydraulic modeling (step d).

OUTCOME OF THIS STEP: A list of representative reaches for each channel type (or channel type bin).

(c) Obtain channel terrain for representative reaches

High resolution channel terrains can be obtained for representative reaches through several options. The necessary spatial resolution of the topographic data depends on the size of the channel and the scale of the biologically relevant hydraulic habitat conditions. For example, 1-m resolution is very detailed for a 40-m wide channel but far too coarse to show spatial variability for a 2-m wide channel. High-resolution channel terrain can be obtained through: (1) existing datasets, (2) model synthesized terrain, or (3) user surveying. The appropriate option depends on available data, resources, and resolution of terrain information needed.

Option 1- Existing Datasets: High resolution channel reach terrains (sub-meter resolution) are under development using Total Station Surveys and LiDAR data for representative reaches in each channel type in classified regions of California (Figure 5). This information will be available in 2021 and will be provided in a supplemental report. The user can also locate existing topographic survey data from other sources.

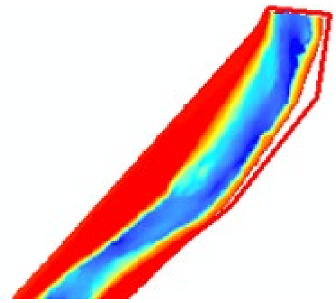

Figure 5. Example 1-m resolution channel terrain developed from a Total Station Survey of a representative reach in the *High width to depth gravel-cobble, pool-riffle* channel type of the South Fork Eel River watershed (see classification in Figure 2).

Option 2- Terrain modeling: Synthetic terrains can be synthesized to represent archetypal channel reach geomorphic attributes using the RiverBuilder software program (Figure 6, Pasternack et al. 2019). RiverBuilder is a user-friendly python-based software program for designing synthetic river channel topography with limited data requirements and expertise. The program is capable of incorporating basic reach-scale channel geometry information and subreach topographic variability attributes to produce rivers with organized, coherent patterns of topographic variability that control geomorphic processes and hydraulic conditions relevant to river ecosystems (Brown et al. 2015; Lane et al. 2018). The program requires input information related to channel slope, sinuosity, channel dimensions (active channel width and depth, width-to-depth ratio), roughness, and geometric representations of sub-reach topographic variability and covariance. These inputs can be based on targeted transect-based field surveys or expert understanding of channel settings, including key topographic controls on hydraulic responses of interest. The scale of topographic variability captured in these terrains should depend on the hydraulic conditions that are relevant to desired ecological outcome.

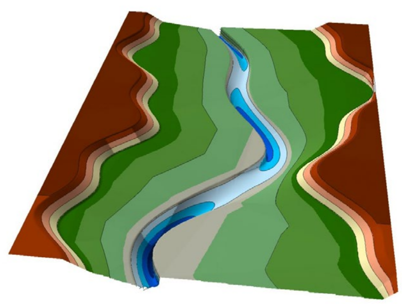

Figure 6. Example channel terrain synthesized using the RiverBuilder model.

Option 3- User-surveyed: The user can generate their own terrain from Total Station Surveying, LiDAR, or other well-documented approaches.

OUTCOME OF THIS STEP: High-resolution terrains for representative reaches in each channel type.

(d) Hydraulic modeling

Hydraulic responses to different discharges can be simulated using one- (1D) or two-dimensional depth-averaged (2D) hydraulic models. 2D modeling is highly recommended here because it retains the complex longitudinal sub-reach variability and complexity, such as observed in eddies, that often drives local hydraulic patterns relevant to aquatic species (Crowder and Diplas 2006). Hydraulic models should be developed for each of the representative channel reaches and run over a range of discharges relevant to the functional flow component and ecological outcome of interest. Hydraulic model inputs include channel terrain (or cross-sections in the case of 1D models) obtained in step c, channel roughness, and upstream discharge and associated downstream water depth boundary conditions for each steady model run. Channel roughness can be estimated using USGS reference images and expert estimation. Rating curves describing the relationship between discharge and water depth can be developed through field measurements or obtained from nearby gaging stations. When rating curves are not available, downstream depth can instead be estimated for discharges of interest using Manning's equation. The specific discharges evaluated should be determined based on the flow magnitude range of the functional flow component and biological conditions of interest. For example, if the focus is on dry season baseflow habitat for native salmonid rearing, model runs should be more highly discretized at low flows and flows above bankfull (and associated terrain information) may not be needed. Finally, it is important to note that the resolution and accuracy of the channel topography from Step c is a major control on how well hydraulic patterns are simulated in this step since hydraulic models, like all modeling efforts, are only as good as their inputs. Results from the hydraulic modeling exercise include depth and velocity rasters (or distributions in the case of 1D models) over a range of discharges for each representative reach (Figure 7).

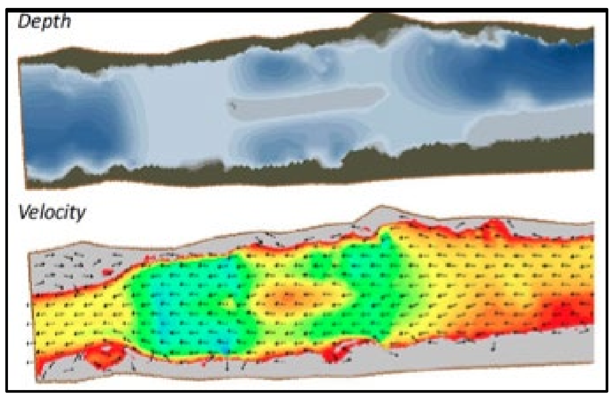

Figure 7. 2D hydraulic model outputs consisting of sub-meter water depth and velocity rasters for a single modeled discharge.

OUTCOME OF THIS STEP: Depth and velocity rasters (or distributions in the case of 1D models) over a range of discharges for each representative reach.

(e) Hydraulic response relationships

Hydraulic response relationships describe the proportion of total cells in the modeled reach exhibiting different values of a hydraulic variable (depth, velocity, shear stress), where the values are scaled by bankfull conditions (e.g. depth / bankfull depth) (Figure 8). These channel type specific relationships can then be extended to other reaches in the stream network in the same channel type (or sub-type).

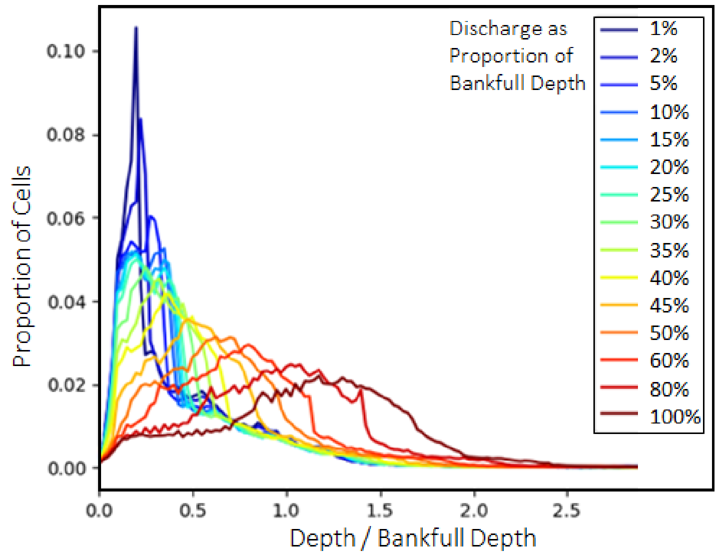

Figure 8. Example hydraulic response relationships for a representative reach in the South Fork Eel River *High width-to-depth gravel-cobble pool-riffle* channel type. Each color represents one of 15 model runs ranging from 1-100% bankfull depth to capture the change in depth distributions with changes in streamflow.

OUTCOME OF THIS STEP: A set of hydraulic rasters and hydraulic response relationships for a desired ecological outcome over a range of relevant discharges for each representative reach.

Refined Ecological Flow Criteria

These hydraulic response relationships and/or information extracted directly from the depth and velocity rasters in the case of 2D modeling can then be linked to habitat preference or tolerance information for species or life-stages of interest. This information can be derived through literature review, expert opinion, or direct field observation. Habitat preference information may already be available for the geographic region or for key species of interest (see *Appendix H - California umbrella fish species*). The result is a set of LOI- and outcome-specific relationships between flow and habitat conditions to facilitate development of refined flow criteria (Figure 1).

The ecological response associated with each discharge may be a single value summarizing the expected suitability of the predicted distribution of hydraulic conditions for the species/life-stage(s) (e.g. a discharge of 0.2 cfs results in 10 m^2 of rearing habitat or 80% of the channel area). Alternatively, a discharge or probability of occurrence of certain life stage may be associated with binary measures such as sufficient or insufficient flow for fish passage, floodplain accessed or not accessed, or more complex measures such as habitat spatial complexity (e.g. Gostner et al 2013), river connectivity metrics related to fish stranding and redd dewatering (e.g. Larrieu et al. 2019), or hydraulic inputs to bioenergetics models (Black et al. 2016).

III. Application

Below, example 2 from Step 8 of the main CEFF guidance document is used to demonstrate an application of this approach.

Background

The SFER watershed in northern California has naturally variable hydrology and limited water storage. Land use is a mix of forest and irrigated agriculture. Upstream of the LOIs, agricultural producers divert or are requesting water right permits to divert water from small tributary streams for irrigation. These diversions affect the water quantity, quality and physical habitat availability for ecological outcomes related to native Coho and Chinook salmonids, including juvenile rearing. Because there are no surface water reservoirs in the system, there is the potential for diversions to significantly extend the duration and reduce the magnitude of dry-season base flows, which can reduce Coho and Chinook rearing and spawning habitat availability. Water managers and stakeholders are in the process of developing environmental flow prescriptions at numerous LOIs throughout the watershed to maintain native salmonid habitat needs while continuing to supply irrigation demands.

In Section A - Step 1 of CEFF, the user identified numerous locations of interest (LOIs) and defined ecological management goals including sustaining juvenile salmonid populations based on discussions with water managers and stakeholders. In Step 2, the user obtained natural ranges of flow metrics. In Step 3, the user determined that the reference flow criteria for dry-season base flow required additional consideration due to potential non-flow factors including geomorphic alteration and reduced riparian vegetation. The user also identified a need for increased specificity in the dry-season baseflow magnitude flow criteria due to high natural variability and an inevitable need for tradeoff analyses in the watershed when developing environmental flow prescriptions due to competition with human water demands during the dry season.

Moving to Section B, in Step 5 a conceptual model was developed linking the focal flow component, dry season base flow, with juvenile salmonid rearing through mediating factors including physical habitat and ecosystem functions. Figure 8 shows a conceptual model for juvenile salmonid growth and survival in the watershed, where the ecological response to Dry Season Base Flows is mediated by hydraulic conditions needed to sustain juvenile rearing habitat over the dry-season. The approach described in this appendix could be used to quantify linkages in this conceptual model.

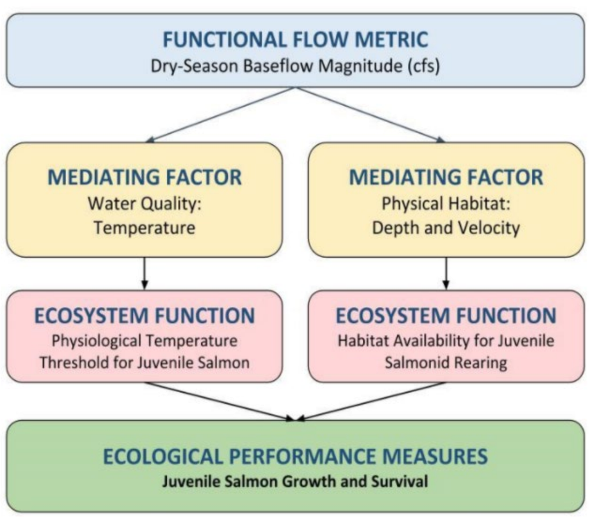

Figure 8. Example CEFF Section B conceptual model linking the focal flow component in a north coast watershed with mediating factors including physical habitat and ecosystem functions including habitat availability for juvenile salmonid rearing, both of which can be quantified using the tools described in this appendix..

Methods

Step a- Geomorphic classification

A geomorphic classification was developed for the SFER watershed as shown in Figure 2 using an approach detailed in Appendix J and Byrne et al. (2020). Seven channel types were identified through statistical analysis of 97 field surveys, ranging from highly confined *high gradient cobble-boulder, step-pool/cascade* tributary reaches to unconfined *gravel, riffle-pool* reaches. An open-source machine learning based predictive model was developed to classify each 200-m interval in the NHDplusV2 stream network for the watershed into one of these seven channel types (Guillon et al 2020).

Step b- Select representative reaches

One representative reach was selected for each of the seven channel types from the set of transect-based field surveys used as input to the classification above. Representative reaches were selected based on if they exhibited geomorphic attributes similar to median conditions for the channel type as well as field accessibility.

Step c- Obtain high-resolution channel terrain

Selecting Option 1 for obtaining high-resolution channel terrain, field-based Total Station Surveys were performed at each representative reach to obtain sub-meter resolution topography that was subsequently processed to generate input terrain for hydraulic modeling (Figure 3).

Step d- Hydraulic modeling

2D hydraulic modeling was performed using TUFLOW HPC (Syme 2001) and Python. TUFLOW is a finite-volume numerical model that solves the Saint-Venant equations for the spatial distribution of water surface elevation, water depth, velocity, and bed shear stress at each computational node. It has been used for a wide variety of applications related to river ecosystems including aquatic physical habitat, flood inundation, sediment transport processes, geomorphic change, and riparian vegetation succession.

Each representative reach hydraulic model was run for 15 discharges, representing the flow needed to fill 1% - 100% bankfull depth. Because the focus was on dry-season baseflows and juvenile salmonid rearing habitat, model runs were more highly discretized at very low flows than flows close to bankfull. In addition to the channel terrains described above, each model run required upstream discharge and associated downstream water stage boundary conditions. Since rating curves between discharge and water stage were not available at the LOIs, discharge was estimated at each water stage associated with a different proportion of bankfull depth using Manning's equation. Roughness (n) and slope (S) were estimated by the user, and a cross-section of the terrain representing a hydraulic control was extracted in ArcGIS to calculate the hydraulic radius (R) and cross-sectional area (A) at each water stage:

$$Q(cfs) = \frac{1.486}{n} AR^{2/3} S_o^{\ 1/2}$$

Step e- Hydraulic response relationships

Hydraulic response relationships were extracted from hydraulic variable rasters generated in step d for each modeled discharge in each channel type, as shown in Figure 5. These channel type specific relationships were then directly extended to all LOIs in the same channel type, resulting in hydraulic response relationships at all LOIs in the geographic region.

Refined ecological flow criteria

Returning to the desired outcome in the SFER of a sustained juvenile steelhead population, the hydraulic response relationships (Figure 9a) were linked with steelhead rearing habitat preferences obtained through a stakeholder working group (Figure 9b). The result was a series of ecological response relationships between dry-season baseflow magnitude and suitable rearing conditions (Figure 9c). Figure 1 shows how these relationships could be used to refine ecological flow criteria and, finally, to generate ecological flow regimes for LOIs across the watershed. Based on stakeholder preferences, these ecological response relationships (Figure 9c) could also be translated into top-down relationships, such as between flow criteria alteration and ecological risk in different water year types (Figure 9d). *Appendix L* describes how these ecological response relationships and ecological flow regimes could be used to evaluate tradeoffs between ecosystem and human water needs to develop environmental flow recommendations as outlied in CEFF Section C.

In the SFER pilot study, flow regime scenarios were generated by adjusting one ecological flow criteria (i.e. dry-season baseflow magnitude) through stakeholder coordination to highlight water management tradeoffs associated with providing a range of juvenile steelhead rearing habitat conditions (low to high probability of occupancy) over the dry-season in specific reaches (LOI) and water year types (WYT). Habitat suitability relationships for juvenile steelhead rearing were already established for the SFER (Figure 9b). The reference ranges for dry season baseflow were calculated at each LOI using modeled daily unimpaired streamflow data. The hydraulic conditions associated with this range of flows was evaluated as described in *Appendix L* to generate LOI-specific relationships between dry-season baseflow and hydraulic conditions relevant to the ecological outcome of interest (i.e. median reach velocity) (Figure 9c). Since different flow criteria alternatives, in this case driven by different diversion limits, result in different changes to the flow metric of interest (i.e. reduction in dry season baseflow magnitude), each management alternative can be assigned to a risk level associated with changes to hydraulic habitat suitability through a top-down risk assessment approach (Figure 3d).

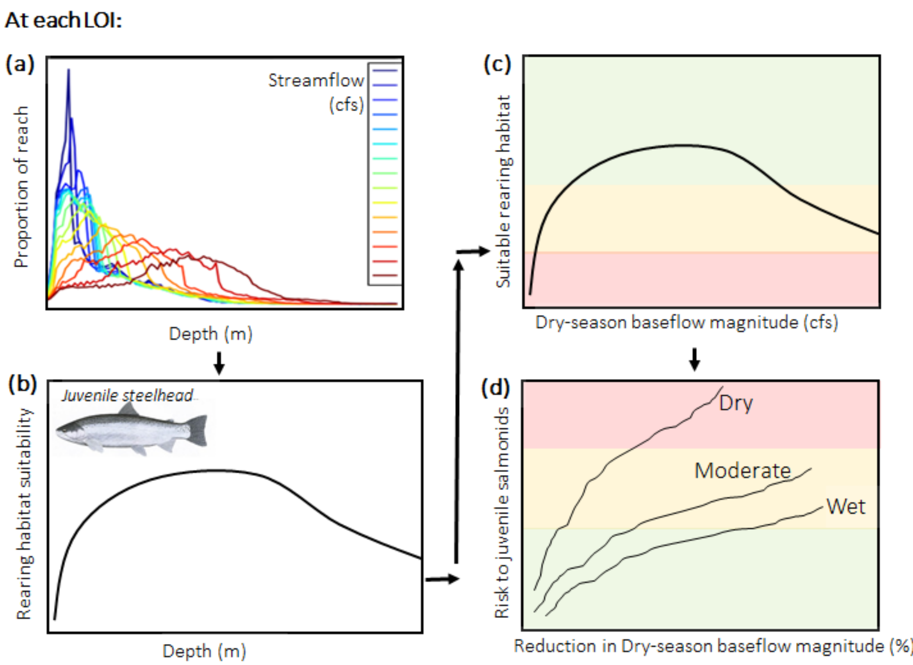

Figure 9. Example of how to combine (a) hydraulic response relationships at each LOI with (b) habitat preference information for a particular species/life-stage to (c) relate distributed ecological response relationships describing the change in suitable habitat conditions with changes in a functional flow metric. These response relationships could be further translated into (d) top-down relationships between alteration in the flow metric and ecological risk in different water year types to facilitate the balancing process in CEFF Section C.

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