RIVER RESTORATION DECISION ANALYSIS - 2D HYDRODYNAMIC APPROACH TO PROJECT PRIORITIZATION

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Abstract: In the field of river restoration sciences there is a growing need for analytical modeling tools and quantitative processes to help identify and prioritize project sites. Two-dimensional (2D) hydraulic models have become more common in recent years and with the availability of robust data sets and computing technology, it is now possible to evaluate large river systems at the reach scale. The Trinity River Restoration Program (TRRP) – Bureau of Reclamation in Northern California is now analyzing a 40 mile segment of the Trinity River to determine priority and implementation sequencing for its Phase II channel rehabilitation projects. A comprehensive approach and quantitative tool has recently been developed to analyze this complex river system. The 2D-Hydrodynamic-Based Logic Modeling (2D-HBLM) tool utilizes various hydraulic output parameters combined with biological, ecological, and physical metrics at user-defined spatial scales and flow discharges to evaluate geomorphic characteristics, riverine processes, and habitat complexity. The habitat metrics are integrated into a comprehensive Logic Model framework to perform statistical analyses to assess project prioritization. The Logic Model will analyze various potential project sites within the 40 mile restoration reach by evaluating connectivity and key response variable drivers. The 2D-HBLM tool will help inform management and decision makers by using a quantitative process to optimize desired response variables with in determining the highest priority locations within the river corridor to implement restoration projects.

Keywords: 2D Hydraulic Modeling, Quantitative Prioritization, Evaluation Metrics, Logic Modeling, Statistical Analysis, and River Restoration

INTRODUCTION

Effective river restoration prioritization starts with well-crafted goals that identify the biological objectives, address underlying causes of habitat change, and recognize that social, economic, and land use issues may constrain restoration options (Beechie et. al. 2008). In addition, effective management actions need to be tied to a Structured Decision Making (SDM) process that connects decisions to objectives (Hammond et al. 1999, Clemen and Reilly 2001). Applying natural resources management actions to the SDM process, like restoration prioritization, is essential for successful project implementation (Conroy and Peterson, 2013; Evers, 2008). This paper describes a river restoration prioritization approach that integrates two-dimensional (2D) hydraulic modeling with desired response and limiting factor metrics into a statistical model framework. This river restoration tool, referred to as two-dimensional hydrodynamic-based logic modeling (2D-HBLM), will analyze and evaluate key biological, physical, and ecological desired responses in relation to various physical and social constraints that may limit restoration options. In this paper, we will demonstrate how this approach can be effectively applied to a large river restoration program to help prioritize projects systematically and objectively.

All too often restoration actions are site specific without considering and evaluating ecosystem scale processes, protection of existing high quality habitats, or an understanding of the effectiveness of specific restoration techniques (Roni et. all. 2002). With over two decades of scientific literature and applied practice, the restoration community has a thorough understanding of the role of channel morphology in the formation of physical habitats (Montgomery and Buffington 1998) and the relationship between flow depth and velocity and habitat quantity and quality (Singh 1989, Lamouroux 1998, Stewart et. al. 2005, Saraeva and Hardy 2009, Goodman et. al. 2014). The understanding of geomorphic processes and physical habitats have been integrated into models to assess hydraulic relationships quantitatively (Schweizer et. al. 2007, Dunbar et. al. 2012) and eco-hydraulic questions through prediction-based simulations (Bovee 1982, Gore et. al. 1998, Milhous et. al. 1989). Model utilization requires restoration science not only to embrace uncertainty (Darby and Sear 2008, Hillman et. al. 2008, Wheaton et. al. 2008), but to integrate bio-physical diversity, variability, and complexity into river management (Brierley and Fryirs 2008). Evaluating tradeoffs and examining alternatives to improve fish habitat through optimization modeling (Null and Lund, 2012) is not just a trend but rather the scientific strategy that management needs to embrace and apply in its decision framework.

The overall approach of this reach-based prioritization is to evaluate the river system through integration of 2D hydraulic modeling, quantitative metric evaluation, and statistical logic modeling within a broader adaptive management and SDM framework. The topics described below include: an overview of 2D hydraulic modeling, the application of the 2D model to the Trinity River, the development of the habitat module quantitative metrics, and the approach to the logic model framework.

OVERVIEW OF 2D HYDRAULIC MODELING

Stream flow modeling is one of the most widely used tools to understand how hydraulic conditions change between discharges and how they are related to fish habitat (Bovee, 1982; Milhous et al., 1989). Building on the early use of one-dimensional (1D) models, 2D hydrodynamic modeling has been widely used for evaluating hydraulic habitat data (e.g. water depth, water velocity, and substrate size). 2D models can be operated on a finer scale than 1D models and they can accurately predict hydraulics in near-shore habitat and across large-scale roughness features (Waddle et al., 2000). 2D models can more accurately predict water velocities and depths at local scales due to the ability to calculate both longitudinal and lateral velocity distributions (Crowder and Diplas, 2000). Sample applications of 2D hydrodynamic models for habitat evaluation include Tharme 2003), Wheaton et al. (2004), Stewart et al. (2005), Mingelbier et al. (2008), Yarnell et al. (2010), Waddle (2010), and Hatten et al. (2013).

In recent years, the trend has been to use a 2D model to represent the roughness elements at the individual boulder scale (e.g., Waddle, 2010), because riverine salmonid species are known to use flow obstructions as velocity shelters in order to minimize energy expenditure while foraging and resting (Bjornn and Reiser, 1991). Boulder placement and the use of large wood are techniques of river restoration commonly used to provide increased diversity of velocity patterns in generally uniform river channels. Accurate modeling of such areas can provide better information about the extent of habitat in rivers and tools for design of constructed habitats.

In this study, we use the U.S. Bureau of Reclamation's Sedimentation and River Hydraulics Two Dimensional depth averaged hydraulic model (SRH-2D). SRH-2D, documented by (Lai 2008; Lai 2010), has been widely used for evaluation of river projects. The robustness and accuracy of SRH-2D have been proven with a wide range of model verifications, as well as many project applications, at both Reclamation and external institutions. SRH-2D has a few unique features which make it ideal for river applications. First, SRH-2D uses a flexible mesh that adopts the arbitrarily shaped element method of Lai et al. (Lai, 2003) for geometric representation. In practice, a hybrid mesh normally uses quadrilaterals in the main stream and near structures and triangles in the floodplain and transition zones. The hybrid mesh achieves the best compromise between accuracy and computing efficiency and such a mesh is relatively easy to generate. Second, SRH-2D adopts very robust (stable) numerical schemes with a seamless wetting-drying algorithm. Reliable solutions may be obtained with the primary tuning parameter of Manning's n. Third, SRH-2D solves the 2D depth-averaged St. Venant dynamic-wave equations using an implicit solution scheme and unstructured meshes with arbitrary mesh cell shapes. It solves both steady and unsteady flows over all flow regimes (subcritical, supercritical or transcritical flows).

APPLICATION OF THE 2D MODEL ON THE TRINITY RIVER

The Trinity River is an ideal location for an applied scientific assessment of a reach based model due to the wealth of robust data sets that span large spatial and temporal scales. The Trinity has been monitored consistently for decades and has been surveyed at high resolution as required for two dimensional hydraulic modeling. A seamless Digital Terrain Model (DTM) that integrates terrestrial and bathymetric topography is the basis of the 40 mile hydraulic model. The DTM for the Trinity consists of airborne LiDAR topography and boat-based sonar bathymetry across the entire reach (Woolpert, 2013) that has been validated within 95% vertical confidence intervals using 0.320-foot RMSEz (Root Mean Square Error) for LiDAR and +/-0.686-foot RMSEz for sonar. This validated accuracy is based on extensive quality control field measurements consisting of 40 channel spanning cross-sections and 849 independent GPS-RTK check shots along the Trinity. The DTM has been certified by a professional licensed land surveyor and exceeds both National Map Accuracy and American Society of Photogrammetry and Remote Sensing (ASPRS) Standards.

In addition to topographic data sets, aerial imagery orthophotography has been collected in multiple years and serves as the foundation data set for geospatial mapping on many projects including the 2D hydraulic model mesh generation. Two model meshes were developed for this project: a coarse mesh to use for model calibration (the calibration mesh) and a denser mesh to use for the actual assessment (the habitat mesh). Both meshes are hybrid meshes that use rectangular elements in the main and side channels and triangular elements in areas that are dry at most flows. The calibration mesh contains one quarter the number of elements as the habitat mesh across the 40 mile reach on the Trinity River.

The calibration mesh was developed from channel bank lines digitized from the aerial imagery data set (Figure 1). The complexity and curvature of the channel dictated the length of elements in a reach. Long straight reaches contain longer elements, Tight bends and areas of complex morphology contain shorter elements.

The width of main channel mesh elements is 1/8 of the local channel width. Side channel

mesh elements are 1/3 of the local side channel width. Calibration mesh elements range from approximately 10 to 50 feet in length and 5 to 25 feet in width. The mean area of calibration mesh elements is 284 square feet.

Figure 1 Comparison of the calibration mesh (left) and the habitat mesh (right)

The habitat mesh was developed by dividing each calibration mesh element into four elements. Channel elements in the habitat mesh range in width from approximately 1 foot to 10 feet. The mean area of habitat mesh channel elements is 71 square feet.

The sole calibration parameter available in SRH-2D is the channel roughness, represented by Manning's n. Increasing channel roughness by increasing the value of Manning's n has the effect of raising the water surface elevation and reducing the flow velocity. Decreasing channel roughness has the opposite effect. The calibration data we used are water surface elevations measured during the bathymetric survey at seven different discharges ranging from 500 cfs to 4500 cfs. About 91% of the model error (modelled elevation minus observed elevation) is within +/- 0.5 feet and the error is symmetrically distributed around zero. This error is similar to the error in the bathymetric data collection.

HABITAT MODULE QUANTITATIVE METRICS

The 2D hydraulic model was run for approximately 20 different discharge cases, ranging from 300 cfs to 14,000 cfs. The hydraulic output of the 2D model is used by a tool called the "Habitat Module to evaluate riverine characteristics using a series of biological, ecological, and physical criteria. The Habitat Module uses quantitative algorithms to calculate key hydraulic variables or "metrics" throughout the river. The metrics are grouped into three spatial output types: 1) Panel-Based "Panel"; 2) Cross-Sectional; and 3) Spatially Distributed - across the mesh elements. For this study, the Panel output was the primary type used. The Panels are 200 meter long and are based off a sampling protocol system currently being used on Trinity for system wide monitoring called Generalized Random Tessellation Stratification (GRTS). Across the entire 40 mile reach, there are 319 Panels from upstream to downstream. The Panel system was used to help organize the hydraulic output and metrics into a uniform system to which further statistical analyses can be applied.

The metrics calculated from the hydraulic model are categorized into three types: Biological, Ecological, and Physical. The other types of information used were field collected empirical data from the Trinity. Table 1 below shows all the available metrics calculated and empirical data that was field measured.

Table 1 Evaluation Metrics from SRH-2D Habitat Module

Metrics calculated from the 2D Hydraulic Model (habitat module)			**Empirical Data**
Physical	**Biological/Ecological**	**Ecological**	**Field Collected**
Depth	Depth/Velocity (DV) -Fry Habitat	Suitable Area for Riparian Regeneration	Redd Locations
Velocity	Cover (C) -Fry Habitat		River Bed Topography Bed Elevation Data (Bathymetry)
Water Surface	Depth/Velocity -Pre Smolt Habitat		
Wetted Edge Length	Cover -Pre Smolt Habitat	Elevation (Delta) Difference between Water Surface and Adjacent Topography	
Shear Stress (avg, StD, etc.)	Depth/Velocity/Cover (DVC) for both Fry and Pre Smolt Habiat		
Stream Power			Bedrock Features
Vorticity	Adult Holding Habitat		Tributaries
Flow Direction/Crossover	Weighted Usable Area (WUA) for Fry and Pre Smolt Habitat – Based on Above Habitat Suitability Criteria (HSC)		Land Ownership
Wetted Area/Wetted XS		Wetted Edge	Infrastructure: including roads, bridges, houses, etc
Sinousity and Thalwag		Wetted Area	
Width/Depth Ratio			

Physical Metrics: Restoration activities on the Trinity River include flow and sediment management intended to promote the dynamic fluvial processes that create diverse physical habitat and rejuvenate the aquatic ecosystem. The physical process metrics used in this study were developed to help quantify the existing geomorphic complexity within each Panel. The fluvial processes involved in the maintenance of high-quality habitat are tightly linked to sediment supply and sediment transport capacity. Scour and fill processes, in which the elevation of the steam bed or bar surface changes dynamically through time, create topographic complexity, maintain substrate quality, and rejuvenate riparian vegetation. Lateral erosion of the banks facilitates planform adjustment and contributes to the formation of alcoves, sloughs, and complex bar features. Although the habitat module cannot address questions about sediment supply, its output includes several metrics intended to assess the spatial variability of sediment transport capacity and geomporhic complexity within each Panel. Shear stress and stream power metrics within each Panel represents the rate of energy dissipation against the bed and banks of a river, which can be used as an indicator of local sediment transport capacity. Using the first derivative of the shear stress can provide an additional metric, which helps determine if the stress in the Panel is increasing or decreasing, providing an indication of where local scour or fill might be expected. The Vorticity metric calculates the angular velocity of a fluid particle and is a kinematic property of the flow field which as a measure of river complexity.

Additional physical metrics include: Flow Direction Change Hydraulic Cross-Over, Wetted Edge Length, Sinousity, Thalweg, etc. For example, Edge Length is the total length of wet-dry boundaries within a panel and reflects complexities of flows around islands, boulders, etc. Various physical metrics can be combined into one representative metric to compare and evaluate the system-wide geomorphic potential or its overall physical complexity at applicable flow discharges. Assessing these metrics in combination can be accomplished using a statistical approach called Principal Components Analysis (PCA). A PCA is used to model variation within a set of metrics to produce a smaller number of independent linear combinations (i.e., principal components; JMP ® 11, SAS Institute, Cary, North Carolina). The first principal component of variables related to geomorphic potential at 6,000 cfs—including velocity, average bed shear stress, average first derivative of shear stress, and stream power—was derived to show the most prominent direction of these metrics using a single variable.

Biological Metrics: A deficit of juvenile rearing habitat has been identified as the primary limiting factor of salmonid populations in the Trinity Rivr and many other rivers. Fry and Pre-smolt critical rearing habitat is computed from the hydraulic model output using Habitat Suitability Criteria (HSC) of derived Depth (D), Velocity (V), and Cover (C). These HSC values were developed for the Trinity River specific to the life stage and species (Goodman et al. 2014). The metric for rearing habitat is fry and Pre Smolt area is based on meeting the depth and velocity combinations (DV) and cover requirements determined by field validated HSC values. The cover criteria are based on field-derived values of suitable distance to vegetation, wood, or other escape cover. The HSC values serve as an index or value range to determine if the habitat is within suitable desirable criteria range for rearing habitat. (See Table 2 below)

Table 2 Trinity River binary habitat suitability criteria from Goodman et al. (2014)

Life stage	Depth	Velocity	Cover
Fry (< 50 mm fork length)	≤ 0.6 meter	≤ 0.15 meters/second	≤ 0.6 meters
Presmolt (50 to 100 mm fork length)	≤ 1.0 meter	≤ 0.24 meters/second	≤ 0.6 meters

The Weighted Useable Area (WUA) metric is a method of combining the scores from the above HSC data for depth, velocity, and cover to evaluate the quality of habitat at a range of values rather than using a binary approach of index cut-off values. WUA habitat values were the primary metric used for the evaluation of biological quality throughout the Trinity system.

APPROACH TO THE LOGIC MODEL FRAMEWORK

The objective of the Logic Model is to assimilate professional judgment, 2D modeling outputs, and empirical data to objectively prioritize restoration projects. Once the hydraulic variables and metrics are calculated within the habitat module and synthesized for each of the 319 Panels. The Logic Model is the component within the 2D-HBLM process that analyses the data statistically and links desired responses with limiting factors to prioritize areas of the river for restoration. Quantitative approaches have long been recognized as a key to improving processes (Box and Myer 1986). Modeling, hierarchical ordering of effects, and identifying key relationships and root causes for deficiency is commonplace in manufacturing (Harry and Schroeder 2006) and increasingly in biological sciences (Dassau et al. 2006; Huang et al. 2009). The Logic Model utilizes such approaches to assess key measures and relationships followed by integration of desired responses and limiting factors to inform prioritization.

Measures used in the Logic Model include physical, biological, and ecological based metrics, along with metrics from empirical data selected using professional judgment prior to analysis. Desired responses include improvements to the quality, connectivity, and complexity of salmonid habitat (Roni et al. 2002). Conversely, limiting factors constrain the ability to implement restoration projects (e.g., access or infrastructure). The distinction between desired responses and limiting factors is important in that the Logic Model is intended to prioritize restoration projects where the need, relative benefit, and practicality are optimized.

Data used in the Logic Model were examined prior to statistical modeling. Both desired responses and limiting factors were reduced to a set of uncorrelated variables using Principal Component Analysis (SAS Institute 2008). This step minimizes the issue of multi-collinearity

in further analyses, particularly with predictor variables (Saab 1999). Desired responses and limiting factors were further analyzed for spatial autocorrelation since standard statistical techniques assume independence among observations. For example, preliminary evaluations show that suitable fry habitat has a partial autocorrelation with at least the two preceding panels at 4500 cfs. Quantitative approaches used in the Logic Model compensate for the relationships among neighboring panels to ensure that parameter estimates and significance tests yield reliable results (Isaak et al. 2010).

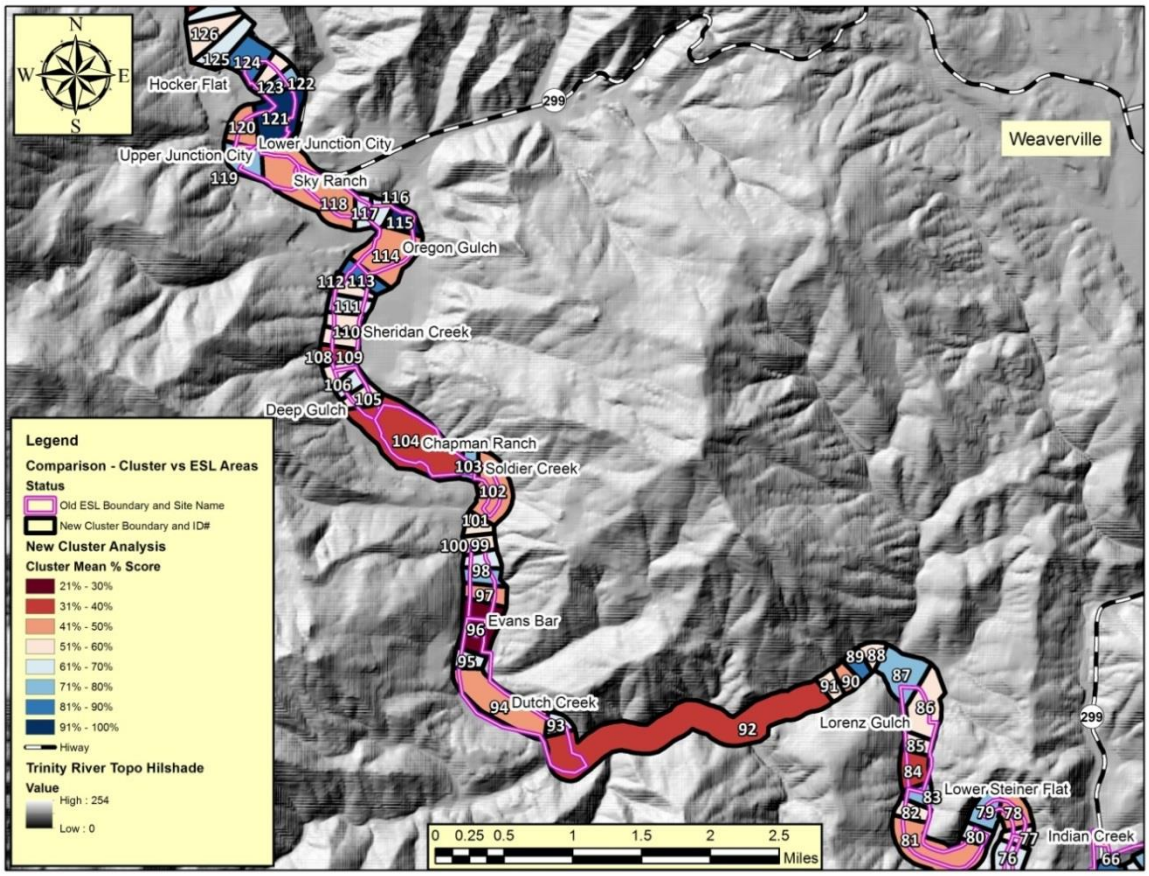
Five metrics were ultimately chosen to be used in the Logic Model analysis to represent biological quality, connectivity, and river complexity, see Table 3 below. Biological quality was defined as the habitat calculated from the weighted usable area (WUA) at winter base flow (300cfs) and at a typical spring flow (1500cfs). Connectivity was defined by the total number of redds observed within each panel and three upstream panels (i.e., a running total of four panels). Complexity was defined by the standard deviation of bed elevation and the standard deviation of stream power at 8,500 cfs. Each panel was ranked relative to the remaining panels (1 to 319) for all five metrics, with ascending ranks for habitat quality and complexity and descending ranks for connectivity (redds). Thus, panels with low WUA values, low variation in complexity, and proximity to a large number of redds would receive lower rankings across the five metrics.

Table 3 Weighting of Metrics Used in the Logic Model in Panel Scoring

Metric	Category	Weight	Relative influence
Rearing Habitat at 300 cfs rank	Habitat Quality (Low Flow)	1.50	0.333
Rearing Habitat at 1,500 cfs rank	Habitat Quality (Mid Flow)	1.00	0.222
Total spawning redds (upstream 3 Panels) rank	Biological Connectivity	1.00	0.222
Standard Deviation of bed elevation (m) rank	Topographic Complexity	0.50	0.111
Standard Deviation of unit stream power (8,500 cfs) rank	Hydraulic Complexity	0.50	0.111

Panels were scored by summing the total ranks across the five metrics, with each metric weighted according to values shown in Table 3. For example, habitat rank at 300 cfs with median accretion has a weighting of 1.50 (33.3% influence), whereas the standard deviation of bed elevation has a weighting of 0.50 (11.1% influence). Each increase in habitat rank and standard deviation of bed elevation rank, therefore, represents a corresponding increase of 1.50 and 0.50 in the total score, respectively. Scores were then scaled relative to the least desirable candidate for a restoration action (i.e., highest score). Scores for each panel, therefore, represent existing habitat quality with the influence of connectivity to spawning habitat and measures of river channel complexity.

Scores across multiple panels were then analyzed to identify segments of the river most suitable for restoration action. First, a cluster analysis (performed by USFWS) was used to identify regions of similar scores that were spatially grouped based on statistical principles from Aldstadt and Getis (2006) and Ord and Getis (1995). The cluster analysis provides a mechanism to evaluate areas desirable for restoration irrespective of arbitrary ESL boundaries. A total of 150 spatially-related clusters of similar scores were identified. The top ten clusters of ascending desirability for restoration action are shown in Table 4 and in Figure 3 below. In addition, these results eliminate any clusters that have less than three adjacent Panels to remove any locations that contain areas that is not practical for restoration actions.



Note: The deeper the color is red the more desirable that location is for restoration; deeper the color is blue the less desirable that location is for restoration. Numbers represent cluster ID that is referenced in the tables below

Figure 2 Map of the new cluster analysis results compared with the old ESL boundaries.

Table 4 Trinity River ESL Segments Ranked by Ascending Desirability for Restoration

Geographic Location	**Evaluation Metric**					**Mean Panel Ranking**	**Additional Considerations for Ranking**				
ESL Name	Rearing Habitat (300cfs)	Rearing Habitat (1500 cfs)	Total Redds (Uprera 3 panels)	SD of Bed Elevation (m)	SD of Unit Stream Power (8,500 cfs)	**Mean Score**	Percent Public Ownership	Adjacent Road Length	Bedrock Area	Topographic Constraint	Geomorphic Potential
Chapman Ranch	85	77	154	69	125	**38.3%**	71%	2,570	0	4.52	-0.46
Below Lorenz (the canyon)	70	59	121	241	217	**43.2%**	58%	2,675	1,084	15.74	1.96
Dutch Creek	103	135	97	149	124	**44.0%**	72%	723	181	7.57	-0.38
Pear Tree Gulch	86	64	173	215	108	**44.2%**	100%	1,354	166	11.95	0.29
Soldier Creek	115	88	150	171	121	**47.0%**	87%	1,151	0	12.39	0.05
Indian Creek (Vitzthum Gulch)	111	115	182	196	103	**51.6%**	64%	2,201	0	7.87	-1.54
Sky Ranch	134	132	97	168	211	**52.2%**	55%	4,464	45	6.34	0.83
Tom Lang Gulch	124	104	176	138	188	**52.9%**	14%	4,426	0	14.59	-0.44
Oregon Gulch	179	177	105	96	114	**55.2%**	60%	3,182	0	3.80	-0.45

Table 4 above, also shows the mean Panel ranking for the five Logic Model metrics along with mean feasibility metrics shown for evaluation. Colors are shaded from red (low scores) to green (high scores) according to ranking scheme described in the approach.

In addition, mean scores were provided across project boundaries (ESLs) to provide context in how river segments used in past evaluations rank under this approach. Metrics judged to be important for assessing project feasibility were calculated based on both clusters and ESLs. These included percent public ownership, road length, bedrock area, topography, and geomorphic potential (the first principal component of velocity, average bed shear stress, average first derivative of shear stress, and stream power at 6,000 cfs). An example of mean feasibility metrics for the identified clusters is shown in Table 5. These metrics are intended to provide additional detail for management's consideration when making final decisions for selecting and prioritizing restoration sites.

Table 5 Top Ten Panel Clusters Ranked by Ascending Desirability for Restoration

Cluster ID	Number of Panels Included	Mean Score	Associated Upstream Project Area (ESL)
96	3	28.7%	Dutch Creek
92	19	35.2%	Below Lorenz (the canyon)
104	7	35.6%	Chapman Ranch
150	7	38.6%	Pear Tree Gulch
60	5	40.2%	Indian Creek (Vitzthum Gulch)
102	4	40.5%	Soldier Creek
114	3	41.3%	Oregon Gulch
94	6	42.7%	Dutch Creek
118	7	45.4%	Sky Ranch
31	4	46.8%	Tom Lang Gulch
Note: See Figure 2 Below for Geographical Representation of the information in this Table			

Table 6 Example of Mean Feasibility Metrics Associated with Clusters

Cluster ID	Associated upstream ESL	Percent Public Ownership	Road Length (ft)	Bedrock Area (ft^3)	Topography ($ft^3 \times 10^6$)	Geomorphic potential (PCA)
96	Dutch Creek	52%	3,719	0	4.6	-0.38
92	Below Lorenz (the canyon)	52%	2,871	1,332	15.8	1.30
104	Chapman Ranch	68%	2,335	0	5.8	-0.52
150	Pear Tree Gulch	100%	2,008	225	12.8	-0.26
60	Indian Creek (Vitzthum Gulch)	89%	1,746	0	7.9	-1.59
102	Soldier Creek	93%	1,052	0	13.3	0.18
114	Oregon Gulch	54%	2,232	0	3.8	-1.43
94	Dutch Creek	77%	-	11	6.3	-0.63
118	Sky Ranch	56%	4,864	153	6.3	0.71
31	Tom Lang Gulch	6%	5,326	0	14.5	-0.70

SUMMARY

The 2D-HBLM process of combining 2D hydraulic modeling output with evaluation metrics and statistical tools is helping bridge new gaps and provide more ways to inform river restoration practitioners and managers. Integrating this model with Adaptive Management Processes and Decision Support Systems can provide the resolution needed for detailed management decisions. 2D-HBLM helps integrate the latest trends in river science and Structured Decision Making processes, allowing for a decision framework that is repeatable, transparent, and quantitative.

Of course, all models have their limitations and therefore the integration between model output and professional judgment is necessary to help validate and ground truth output results. On the Trinity, the entire 2D-HBLM process incorporated many partner organizations and agencies that helped foster a collaborative multi-disciplinary effort. The output results from the cluster analysis were informally validated by technical experts from various disciplines including: fishery biology, geomorphology, and hydraulic engineering with expert knowledge of the Trinity River system. The cluster analysis results matched closely with professional judgment and gave the technical team confidence in making final recommendations to management.

The results from the 2D-HBLM framework were applied to the Trinity River Restoration Program through a collaborative adaptive management process. The results of the model were integrated through the re-defining the prioritization of channel rehabilitation project sites designs that were being scheduled for the 2015 calendar year. The final 2D-HBLM cluster analysis results were refined based on professional judgment from internal team members through the technical workgroup process. The team members took into account other factors like constructability, site access logistics, as well as, relationship factors such as site interdependence and geographic affiliation. Contiguous projects would help increase design efficiency and create synergy among projects and design teams. Therefore out of the recommended clusters, the Trinity River Restoration Program – Design Team recommended to management to select clusters: 104 through 114 (Chapman Ranch through Oregon Gulch) and the top ranking cluster - 96 (Dutch Creek/Upper Evans Bar). Management agreed to adopt the technical recommendation and therefore the project sites are currently in the design process. This new approach to project prioritization was implemented successfully through the diverse stakeholder partnership of the TRRP and has provided improved technical transparency and decision making defensibility.

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