Title
Automating flood-safe ecological river modelling and design

Permalink
https://escholarship.org/uc/item/8w1903bt

ISBN
9780367627737

Authors
Schwindt, S
Pasternack, GB

Publication Date
2020

River Flow 2020 – Uijttewaal et al (eds)
© 2020 Taylor & Francis Group, London, ISBN 978-0-367-62773-7

Automating flood-safe ecological river modelling and design

Sebastian Schwindt
Institute for Modelling Hydraulic and Environmental Systems, University of Stuttgart, Stuttgart, Germany

Gregory B. Pasternack
Department of Land, Air and Water Resources, University of California, Davis, CA, USA

ABSTRACT: River restoration projects with the goals of habitat enhancement and improved flood protection involve ecological, structural, and socio-economic river design. The current best practice virtually assesses the hydro-geo-climatic river landscape with remote sensing techniques and two-dimensional numerical modelling. The resulting data inform the flood-safe design of ecohydraulically viable river design features. Here, we demonstrate the application of a novel algorithm for programmatic river landscape optimization as a function of seasonal habitat area gained, physical stability during floods, and construction costs. In a case study on California's Yuba River (USA), we illustrate the design of an artificial side channel for enhancing the habitat for Pacific salmon. We show that the placement of nature-based engineering, such as native vegetation plantings or large wood can be almost completely automated. In contrast, the automated optimization of ecologically valuable terraforms (self-sustaining morphodynamic structures) remains a challenge for future numerical models and design algorithms.

1 INTRODUCTION

Humanity has been using the watercourses of the earth since antiquity (Mays, 2008). In the last centuries, river modifications stipulated channel rectifications and monotone stream patterns to the benefits of economy. The anthropogenic alterations of fluvial landscapes nowadays cause flooding problems and eco-morphological discontinuities between rivers and floodplains (Stone, et al., 2017). Countermeasures require sustainable river design concepts with clear definitions of goals and success parameters (Rinaldi, et al., 2017). This study demonstrates the application of a novel programmatic design concept for long-living habitat enhancement features that employs expertise in hydraulic engineering, geomorphology and ecohydraulics/biology. The design process starts with river landscape assessments, including topography, hydrology, substrate, and vegetation. Such information constitutes boundary and initial conditions for numerical models that produce hydraulic parameter maps. The hydro-topographic and substrate data are the input for the programmatic habitat enhancement design. We demonstrate the programmatic, half-automated design concept with a case study at California's lower Yuba River (USA).

2 SITE DESCRIPTION AND PROJECT GOALS

The lower Yuba River is located in Northern California, USA (Figure 1), and subject to scientific studies for a couple of decades already. Mining activities, followed by the construction of large dams, first led to sediment excess, then to a complete cut-off of the sediment supply. Yet the river is an important reproduction site for Pacific salmon (Pasternack, et al., 2010). Within the California Environmental Quality Act (CEQA), private and public actors as well as

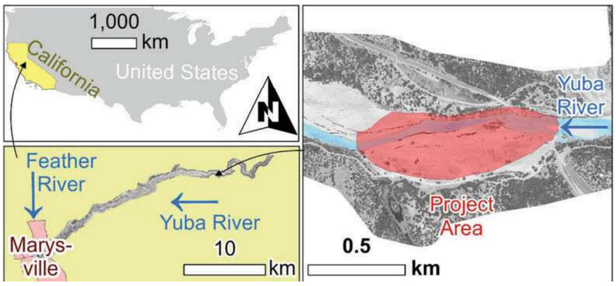


Figure 1. Location of the project area at California's lower Yuba River.

Figure 2. Picture of the project site, view in upstream direction (source: Sebastian Schwindt 2017).

research institutions are working on the maintenance and enhancement of habitat conditions for salmonids, notably Chinook salmon (*Oncorhynchus tshawytscha*) and anadromous steelhead (*Oncorhynchus mykiss*). The design challenge is to create high quality salmonid habitat that also lasts for a long time. To this end, several dozens of project proposals have been prepared in the past. Here we present the application of a novel science-based approach to create instream and floodplain habitat. We apply two-dimensional (2D) numerical models on a river length of about one kilometer to improve instream salmonid habitat with an artificial side channel. In addition, we use nature-based engineering to enhance the habitat of the floodplain with the novel river design software *River Architect*.

The project area is located at a splay downstream of a highway bridge (see Figure 2), where the average channel width (mean annual discharge) and slope are approximately 75 m and 0.35%, respectively. The mean surface grain size is approximately 0.11 m. The baseflow and mean annual discharge are approximately 25 m^3/s and 64 m^3/s, respectively. Flood discharges of 965 m^3/s, 1714 m^3/s, and 4727 m^3/s have recurrence periods of 5, 10, and 50 years, respectively.

3 METHODS

3.1 *Terrain assessment and 2D hydrodynamic modelling provide design input data*

The terrain topography and bathymetry of the lower Yuba River stem from LiDAR and SoNAR survey data. In addition to the DEM, we use detrended elevations, which correspond to the terrain DEM minus the closest point of the channel Thalweg. The detrended DEM shows for example the magnitude of bar and floodplain heights, which is important to identify disconnected habitat.

Surface grain size classes of the entire lower Yuba River were mapped in 2006/2008 (Jackson, et al., 2013). However, grain sizes supposedly changed significantly compared with when they were mapped and we are currently re-creating grain size maps from 2018 with high-resolution LiDAR imagery (Diaz-Gomez, et al., 2019).

We use TUFLOW (2018) GPU for 2D hydrodynamic modelling of steady flow conditions at 23 discharges ranging from below baseflow to a 50-years flood event (15-4727 m^3/s). Elevations of 2D mesh cell centers, sides, and corners result from a 2017 DEM. A regular fixed square grid with a mesh size of 0.9 m applies to discharges of less than 1000 m^3/s, and a mesh size of 9 m applies to higher discharges. A globally optimized, constant Manning's *n* of 0.035 s/m$^{1/3}$ accounts for surface roughness, where vegetation roughness is not considered. The model was calibrated and validated with 8.06·106 LiDAR points, 256 wading measurements, and 9389 kayak measurements (Barker, et al., 2018).

To enable the meaningful placement of vegetation plantings and other river design features, we use a morphological unit classification (Wyrick & Pasternack, 2016), which delineates the following apparent instream landforms at the scale of 0.1 to 10 channel widths as a function of flow depth and velocity: chutes, glides, plane bed, pools, riffles, riffle transitions, runs, slackwater and steps.

Indigenous plant species are phreatophytes, which need to be close enough (vertically) to the groundwater table to survive dry seasons. Therefore, we use depth to groundwater rasters that result from the subtraction of the baseflow water surface elevation from the DEM. The hypothesis is that the terrain in vicinity of the river is saturated with water up to the baseflow water surface elevation.

3.2 *River design features enhance habitat*

Rivers can be modified on a segment scale or on a section to reach scale. On the segment scale, the longitudinal connectivity of rivers can be improved through discharge or sediment budget alterations. Examples are flow regulations of dam releases (environmental flows), the removal of artificial lateral barriers (dams or sills), or sediment replenishment (Acreman, et al., 2014). Here, we will not use segment-scale features because of higher-order implications driven by economic and political decision-making on environmental policy and dam regulation. We only consider habitat enhancing river design features that apply to section to reach-scale extents with 1-100 times the river width. Such technically explicit interventions imply terraforming and the subsequent application of nature-based engineering to stabilize new terraforms.

Terraforming includes all types of earth movements such as creating artificial side channels, calm water zones, side cavities, widening of the riverbed, grading of floodplains or other instream bedforms that provide beneficial habitat conditions.

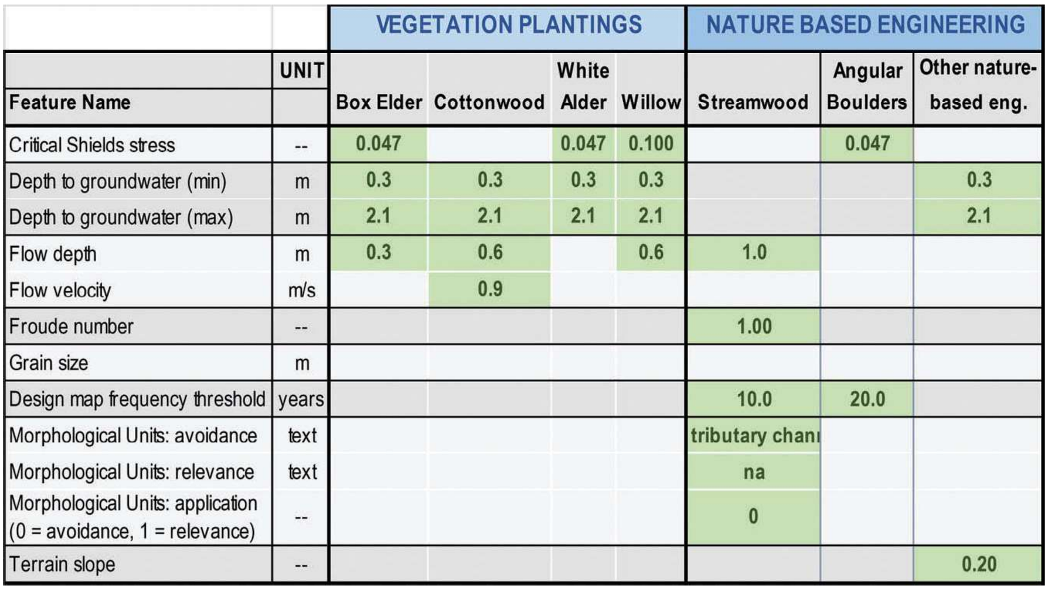
Nature-based engineering stabilizes new habitat enhancing terraforms. The most efficient nature-based engineering feature is the plantation of indigenous vegetation that grows bank strength and provides cover habitat (local flow field perturbation and fish shelter) over time. Young plants may require additional stabilization in their early growth phase and soil bioengineering (e.g., geotextiles or large wood) can be used to yield the required stability. Moreover, angular boulders may be placed in regions where hydraulic forces are high (indicated by 2D modelling results) (Schwindt, et al., 2019).

3.3 *Lifespan mapping indicates physical feature longevity*

Terraforming and nature-based engineering features can be classified by survival thresholds that drive their physical survival. If a pixel of a hydraulic raster (discharge-specific) exceeds the survival threshold value, a feature can be expected to fail. When multiple discharges are modeled with a 2D hydrodynamic model, the (flood) return periods of these discharges determine the feature lifespans (Schwindt, et al., 2019). Table 1 summarizes the threshold values of terraforming and nature-based river design features applied in this study.

The modeled pixel-wise values of hydraulic parameters (Shields stress, flow depth and velocity, and Froude number) is vetted against survival thresholds of applicable features (Table 1) to identify the lowest discharge at which a feature fails (per pixel). The return period of the highest discharge at which a feature does not fail on a pixel defines the lifespan of that feature at a pixel (Schwindt, et al., 2019).

Table 1. Threshold values used for four indigenous plant species and nature-based engineering features (extracted from Schwindt, et al., 2019).



		VEGETATION PLANTINGS				NATURE BASED ENGINEERING		
Feature Name	UNIT	Box Elder	Cottonwood	White Alder	Willow	Streamwood	Angular Boulders	Other nature-based eng.
Critical Shields stress	--	0.047		0.047	0.100		0.047	
Depth to groundwater (min)	m	0.3	0.3	0.3	0.3			0.3
Depth to groundwater (max)	m	2.1	2.1	2.1	2.1			2.1
Flow depth	m	0.3	0.6		0.6	1.0		
Flow velocity	m/s		0.9					
Froude number	--					1.00		
Grain size	m							
Design map frequency threshold	years					10.0	20.0	
Morphological Units: avoidance	text					tributary chan		
Morphological Units: relevance	text					na		
Morphological Units: application (0 = avoidance, 1 = relevance)	--					0		
Terrain slope	--							0.20

3.4 *Ecohydraulic functions evaluate habitat conditions*

Habitat preferences of target aquatic species can be assessed as a function of flow depth and velocity to calculate a dimensionless Habitat Suitability Index *HSI* (Bovee, 1986; Stalnaker, et al., 1995). The discharge-dependent flow depth and velocity rasters result from the 2D hydrodynamic model. Habitat suitability functions assign *HSI* values as a function of preferred depths and velocities for target fish species and lifestage. The *HSI* ranges from 0.0, indicating avoided habitat, to 1.0, indicating preferred habitat. Figure 3 shows exemplary Depth Habitat Suitability Index *DHSI* and Velocity Habitat Suitability Index *VHSI* curves for juvenile Chinook salmon.

Both *DHSI* and *VHSI* can be combined as their product, using fuzzy logics, their arithmetic mean, or the geometric mean. In the following, we use the geometric mean:

$$cHSI = \sqrt{DHSI.VHSI} \tag{1}$$

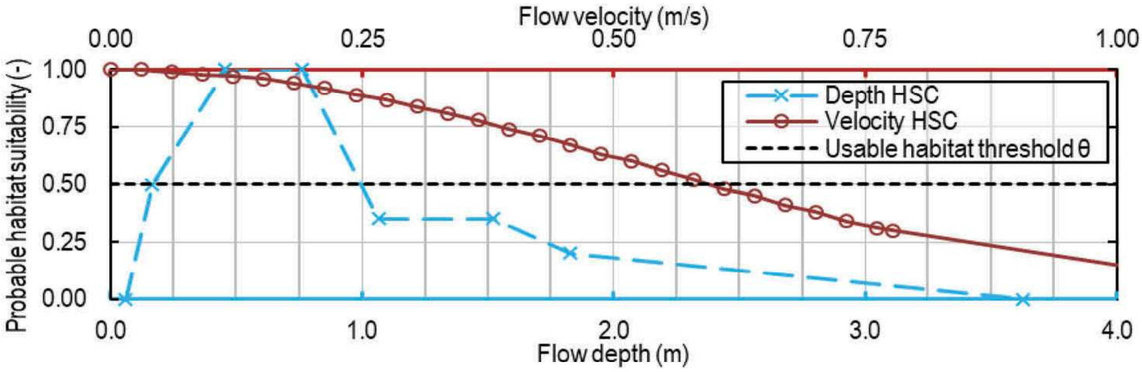


Figure 3. Depth Habitat Suitability Curves for juvenile Chinook salmon in the lower Yuba River (source: Schwindt, et al., 2019).

The planning of habitat enhancement measures for spawning, fry and juvenile lifestages requires that river design features improve the velocity and depth pattern for relevant discharges during months when those lifestages are present in the river. To consider season-specific discharges only, based on a discharge's probability of occurrence, we use flow duration curves that limit to specific seasons of lifestages of the target fish species (Chinook salmon) juvenile lifestage. Therefore, we extract flow data from 15. June to 29. November only from a 40-years flow record with daily average discharge data. For every discharge, we consider the sum of all *cHSI* pixels larger than a threshold value ϑ (here: $\vartheta = 0.5$), as usable juvenile salmonid habitat area. Every *cHSI* raster is associated with discharges that occur during a fish-lifestage season. The seasonal exceedance duration probability p_{Qk} (corresponding to days per season that a discharge is present) of each relevant discharge Q_k multiplied with the associated usable habitat area ($cHSI > \vartheta$) is the Seasonal Habitat Area (*SHArea*) in m^2 per year (Schwindt, et al., 2020).

3.5 *Design automation enables project efficiency optimization*

The project efficiency is here defined as the ratio of estimated project costs (in US $) and the net gain in *SHArea* (in m^2) to evaluate the estimated habitat enhancement success. Project costs stem from area values of applicable features and excavation/fill volumes (in m^3) for terraforming. We use the open-source Python3-based software "*River Architect*" (Schwindt, et al., 2020) for terraforming assessment, automated placement of nature-based engineering features, ecohydraulic evaluation and calculation of the project efficiency metric. The design is an iterative process that involves:

- A terraform optimization iteration:
  - Identify best lifespans of terraforming features and modify terrain with computer-aided drawing;
  - Re-run 2D hydrodynamic model with modified terrain for verification of habitat benefits and flood resilience;
  - Adapt terraforms as a function of 2D hydrodynamic modelling to optimize habitat for target fish species and lifestages as a function of *DHSI* and *VHSI*;
    - ➔ Iterate to maximize usable habitat area for target discharges (season-driven).
- The placement of vegetation plantings & nature-based engineering:
  - Add indigenous plantings based on best lifespan maps showing most relevant species;
  - Add supporting nature-based engineering where vegetation planting lifespans are low (< 2.5 years);
    - Preferably use large wood to support plantings;
    - Use angular boulders to support living nature-based engineering features where large wood stability is low;
  - Stabilize new steep slopes (> 20%) with nature-based engineering features.
- The comparison of ecohydraulic benefits (*SHArea* before and after project implementation).
- The calculation of costs for project implementation as function of mass movement volumes, vegetation plantings area and nature-based engineering quantities.

More information about *River Architect* and its application is available on their website (https://riverarchitect.github.io).

4 RESULTS: SIDE CHANNEL AND FLOODPLAIN HABITAT OPTIMIZATION

The river splay (Figure 1) makes the site suitable for turning a current flood runner (activates for discharges of more than 245 m^3/s) into a permanent side channel. The terraforming plan follows design criteria for stable side channels (Van Denderen, et al., 2018) with an inlet that bifurcates the main stream in a 40°-50° angle to force flow separation into the main channel

(Figure 4). The inlet bottom is at 59 m a.s.l. to yield flow depths between 0.1 m to 1.0 m for mean annual flow conditions (discharge of 64 m³/s). The side channel bottom of the outlet is at 56.5 m a.s.l. The Thalweg lengths of the main and side channels are both approximately 730 m. The equal lengths of the main and side channel are applicable because of a steep riffle in the main channel, directly downstream of the bifurcation. Thus, the main channel is unlikely to be cut-off by the side channel because the sediment transport capacity of the main channel will dominate (Van Denderen, et al., 2018).

An ecologically advantageous and self-maintaining pool-riffle pattern constitutes the side channel bed, where the target velocity reversal is at 1/3 times a 2-years flood of approximately 311 m³/s (i.e., 311 m³/s in the new side channel). The corresponding normal flow section of the inlet is characterized by a trapezoidal cross-section with a base width of 21 m, a bank slope of 1:2.5 (V:H), and a flow depth of approximately 2 m at the target reversal discharge. The morphological sustainability of the artificially created pool-riffle pattern is provided by respecting a flow velocity reversal criterion (Caamaño, et al., 2009) with a target pool depth of $\Delta z \approx 0.3$ m. The design criteria were calculated with the *River Architect*. The 2D model shows that the new island is completely flooded when the discharge exceeds 965 m³/s (5-years flood). The model also confirms the desired functionality of the flow bifurcation angle (flow separation in the main channel). In the absence of a morphodynamic model, however, it should be noted that the functionality (self-maintenance) and longevity of the side channel cannot be proven.

The necessary terraforming actions involve excavation on the order of $105 \cdot 10^3$ m³ of gravel and cobble, while approximately $8 \cdot 10^3$ m³ of the sediment can be directly reused for fill on-site. Thus, excavation dominates fill by approximately $97 \cdot 10^3$ m³. The material (gravel and cobble) surplus may be used for filling deep gold mining pits up to preferred water depths of salmonids at other sites.

The newly created island is designed for hosting indigenous plantings with adequate depths to the groundwater. Thus, indigenous vegetation plantings and nature-based engineering features will enhance the sustainability of the side channel through the stabilization of the new island and the left side channel bank (Nanson & Knighton, 1996). Figure 5 maps the most sustainable vegetation plantings, necessary stabilization features in terms of large wood, and angular boulders (automatically created with *River Architect*). Anchored logs and angular boulders reinforce the side channel intake. No large roughness element is placed in the side channel to ensure its hydraulic functionality.

The measure creates $2.0 \cdot 10^3$ m² of *SHArea* for juvenile Chinook salmon. Figure 6 compares the 2017 situation of the site with the As-Built project situation. The As-Built project will provide up to 1.3 times more usable area for the juvenile lifestages for discharges below 57 m³/s.

Table 2 summarizes actions, construction costs of US $ $13{,}461 \cdot 10^3$ and the ecological trade-off of the modifications. The project efficiency can be evaluated by the monetary costs per unit habitat area gained for a target fish species, which corresponds here to US $ 6,652 per m² *SHArea* gained for juvenile salmonids.

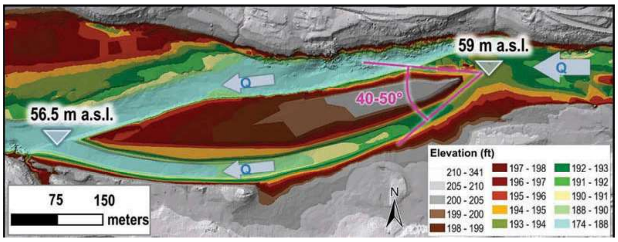


Figure 4. Side channel concept for juvenile salmonid habitat enhancement at the project site. The side channel results from grading the current flood runner (lower “Q” arrow in the figure). The bifurcation angle (in purple) between 40° and 50° with a bottom elevation of 59 m a.s.l. (194 ft) enhance the sustainability of the side channel.

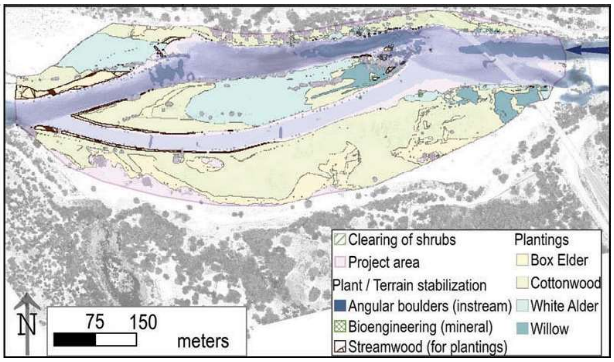


Figure 5. Map of vegetation plantings and other nature-based engineering features based on best lifespan maps after terraforming. The blue arrows and area indicate flow directions and the wetted area at a discharge of 85 m³/s.

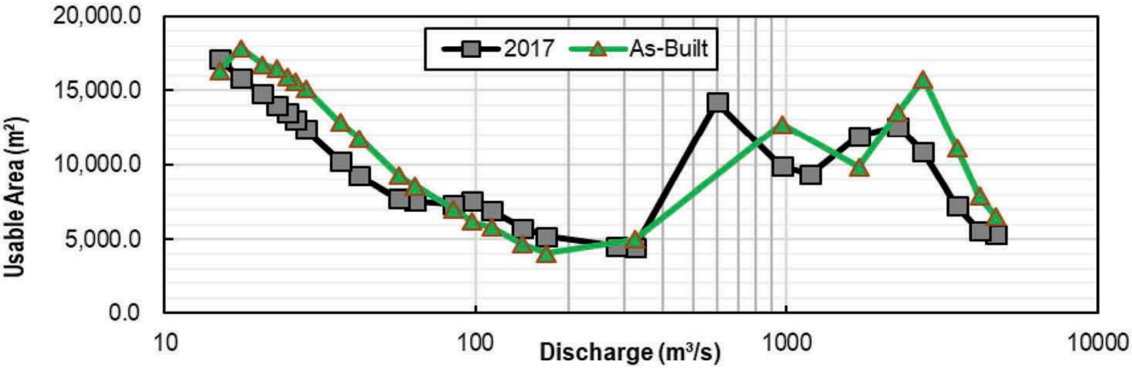


Figure 6. Preferred habitat area for juvenile Chinook salmon as a function of discharge for the 2017 and As-Built conditions.

5 DISCUSSION

Figure 7 maps the presence of preferred usable habitat area for a discharge of 42 m³/s, which corresponds to the dominant discharge in the season (June until November) of juvenile Chinook salmon presence.

The figure shows relatively low habitat quality in the new side channel, owing to the complexity of combined velocity-depth effects that can hardly be optimized by expert-driven, manual drawing of terraforms. More sophisticated planning tools, such as *River Builder* (Brown, et al., 2014), may increase usable habitat area in the side channel in the order of $100 \cdot 10^3$ m² to $130 \cdot 10^3$ m² (total wetted project area at 42 m³/s). However, such tools still need development to make the link between synthetic landscape creation and present hydro-climatic conditions. The conceptualization and ultimate verification of artificially designed, habitat enhancing, and self-maintaining morphodynamic structures additionally requires

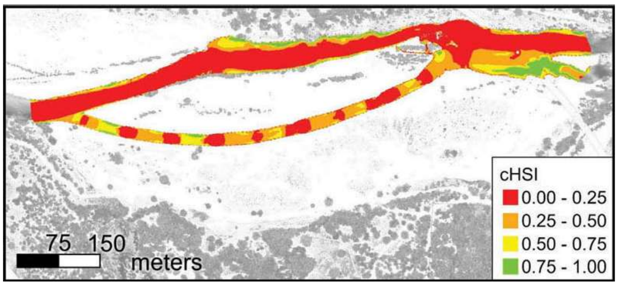


Figure 7. Combined Habitat Suitability Index (cHSI) map before (2017) and with implementation (As-Built) at a discharge of 42 m³/s (flow direction from right to left).

Table 2. Quantities, estimated costs (exemplary) and ecological trade-off of the habitat enhancement measure.

Position	Quantity	Unit	Costs (US $)
Terraforming (excavation dominates)	$97 \cdot 10^3$	m^3	$3,212,032.86
Vegetation Plantings	$163.3 \cdot 10^3$	m^2	$1,629,860.04
Stabilization of Vegetation Plantings	div.	div.	$693,375.00
Nature-based engineering (other)	$12.2 \cdot 10^3$	m^2	$2,313,937.50
Civil engineering	20	%	$1,569,841.08
Fees and Licensing	51.5	%	$4,042,340.78
Estimated Total Costs			**$13,461,387.27**
Net Gain in Seasonal Habitat Area (*SHArea*)	$2.0 \cdot 10^3$	m^2	$13,461,387.27
Cost per m^2 SHArea	**1**	**m^2**	**$6,652.76**

morphodynamic models and modelling unsteady flow scenarios. Variable discharge sequences are necessary to model flood hysteresis and habitat (dis-) connectivity in combination with hydro-peaking from upstream dams (Larrieu, et al., 2019).

6 CONCLUSIONS

The design of artificial river landscapes for enhancing aquatic habitat for target species can be partially automated with currently available software. Nature-based engineering features such as vegetation plantings and the placement of large wood can already be integrated with the design automation tool *River Architect*. However, terraform optimization to yield preferable flow depths and velocities for target fish species requires improvement of the application of numerical models and their outputs.

This work is funded by the Yuba County Water Agency (Marysville, California, USA; Award #201016094 and Award #10446) and USDA National Institute of Food and Agriculture, Hatch project number #CA-D-LAW-7034-H.

REFERENCES

Acreman, M. et al., 2014. Environmental flows for natural, hybrid, and novel riverine ecosystems in a changing world. *Frontiers in Ecology and the Environment*, Volume 12, pp. 466–473.

Barker, J. R. et al., 2018. Kayak drifter surface velocity observation for 2D hydraulic model validation. *River Research and Applications*, Volume [in press], pp. 1–11.

Bovee, K. D., 1986. *Development and evaluation of Habitat Suitability Criteria for use in the instream flow incremental methodology*, Fort Collins, CO, USA.

Brown, R. A., Pasternack, G. B. & Wallender, W. W., 2014. Synthetic river valleys: Creating prescribed topography for form–process inquiry and river rehabilitation design. *Geomorphology*, Volume 240, pp. 40–55.

Caamaño, D. et al., 2009. Unifying Criterion for the Velocity Reversal Hypothesis in Gravel-Bed Rivers. *Journal of Hydraulic Engineering*, Volume 135, pp. 66–70.

Diaz-Gomez, R. et al., 2019. *Can airborne lidar point clouds quantify grain size contributions to ground sediment facies?*. San Francisco, CA, USA.

Jackson, J. R., Pasternack, G. B. & Wyrick, R., 2013. *Lower Yuba River Accord Monitoring and Evaluation program: Substrate of the Lower Yuba River*, Davis, CA, USA.

Larrieu, K., Schwindt, S. & Pasternack, G. B., 2019. *Automated Ecohydraulic Assessment of River Connectivity Identifies Fish Stranding and Redd Dewatering Risks*. San Francisco.

Mays, L. W., 2008. A very brief history of hydraulic technology during antiquity. *Environmental Fluid Mechanics*, Volume 8, pp. 471–484.

Nanson, G. C. & Knighton, A. D., 1996. Anabranching Rivers: Their cause, character and classification. *Earth Surface Processes and Landforms*, Volume 21, pp. 217–239.

Pasternack, G. B., Morford, S. L. & Fulton, A. A., 2010. Yuba River analysis aims to aid spring-run chinook salmon habitat rehabilitation. *California Agriculture*, Volume 64, pp. 69–77.

Rinaldi, M. et al., 2017. New tools for the hydromorphological assessment and monitoring of European streams. *Journal of Environmental Management*, Volume 202, pp. 363–378.

Schwindt, S., Larrieu, K. & Pasternack, G. B., 2019. *River Architect - A Python-based tool set for river design, restoration, and ecohydraulic assessments*, https://riverarchitect.github.io.

Schwindt, S., Larrieu, K., Pasternack, G. B. & Rabone, G., 2020. River Architect. *Software X (accepted)*.

Schwindt, S. et al., 2019. Hydro-morphological parameters generate lifespan maps for stream restoration management. *Journal of Environmental Management*, Volume 232, pp. 475–489.

Stalnaker, C. et al., 1995. *The Instream Flow Incremental Methodology - A Primer for IFIM*. Washington, D.C., USA: National Biological Service, U.S. Department of the Interior, Opler, Paul A. and Rockwell, Elizabeth D. and Zuboy, James R. and Cox, Jerry D. and Harris, Deborah K. (eds.).

Stone, M., Byrne, C. & Morrison, R., 2017. Evaluating the Impacts of Hydrologic and Geomorphic Alterations on Floodplain Connectivity: Floodplain Connectivity. *Ecohydrology*, Volume 10.

Van Denderen, R. P. et al., 2018. Morphodynamic assessment of side channel systems using a simple one-dimensional bifurcation model and a comparison with aerial images. *Earth Surface Processes and Landforms*, Volume [in press], p. 14.

Wyrick, J. R. & Pasternack, G. B., 2016. Revealing the natural complexity of topographic change processes through repeat surveys and decision-tree classification. *Earth Surface Processes and Landforms*, Volume 41, pp. 723–737.