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Hydro-morphological parameters generate lifespan maps for stream restoration management

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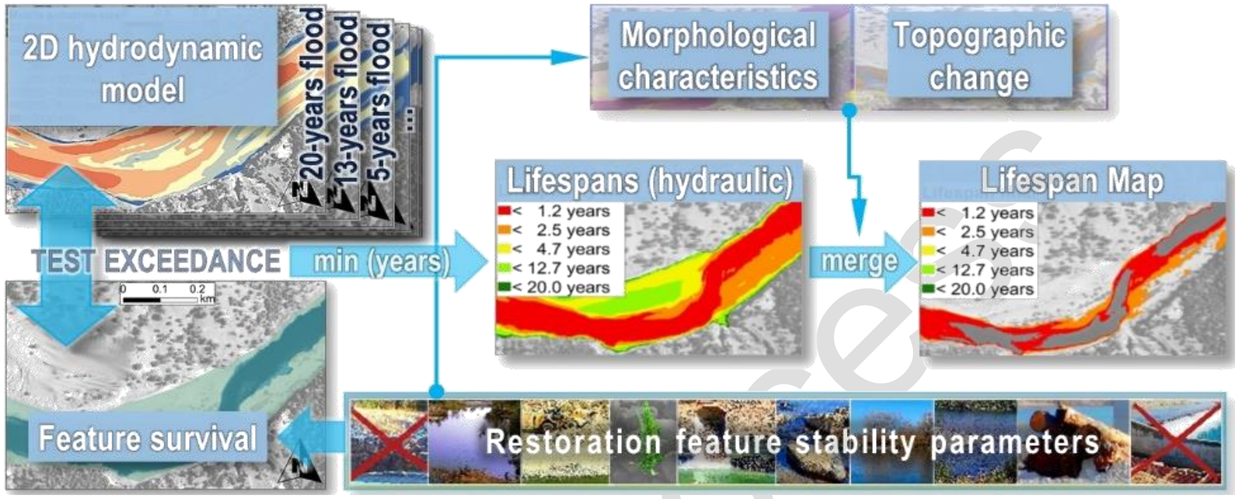

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Abstract

Anthropogenic, eco-morphological degradation of lotic waters necessitates laws, directives, and voluntary actions involving stream restoration and habitat enhancement. Research and engineering efforts are establishing a vast number of stream restoration planning approaches, design testing frameworks, construction techniques, and performance evaluation methods. As the practice of restoration scales up from an individual action at a single site to sequences of actions at many sites in a long river segment, a primary question arises as to the lifespan of such a sequence. This study develops a new framework to identify relevant parameters, design criteria and survival thresholds for ten multidisciplinary restoration techniques, adequate for site-scale to segment-scale application, in a comprehensive review: (1) bar and floodplain grading; (2) berm setback; (3) vegetation plantings; (4) riprap placement; (5) sediment replenishment; (6) side cavities; (7) side channel and anabranches; (8) streambed reshaping; (9) structure removal; and (10) placement of wood in the shape of engineered logjams and rootstocks. Survival thresholds are applied to a sequence of proposed habitat enhancement features for the lower Yuba River in California, USA. Spatially explicit hydraulic and sediment data, together with numerical model predictions of the measures, were vetted against the survival thresholds to produce discharge-dependent lifespan maps. Discharges related to specific flood-return periods enabled probabilistic estimates of the longevity of particular design features. Thus, the lifespan maps indicate the temporal stability of particular stream restoration and habitat enhancement features and techniques. Areas with particularly low or high lifespans help planners optimise the design and positioning of restoration features.

Keywords: Eco-morphology; habitat enhancement; river management; stream restoration; sustainability.

1. Introduction

Throughout history, wide-ranging river rectifications and monotone stream patterns have been engineered for economic benefits, such as the conversion of the Rhine River into a navigable channel (Tulla, 1812). Today, many eco-morphological problems resulting from stream rectification are considered serious impacts on stream ecology, ecosystem services, and the broader economy (e.g., devastating floods) (Blackbourn, 2006; Surian and Rinaldi, 2003). Consequently, governments write laws, issue directives, and fund voluntary actions involving stream restoration and habitat enhancement (e.g., the U.S. National Environmental Policy Act 1969; Canadian Environmental Protection Act 1999; European Water Framework Directive 2000). Wohl et al. (2015) summarised the state of science and practice of stream restoration in a review of small, medium and large rivers. They identified useful paradigms for the planning of habitat enhancement projects. Technical features of stream restoration were documented in several studies (e.g., Bernhardt et al., 2005; Morandi et al., 2014; Wohl et al., 2015) and a multitude of assessment strategies are available (e.g., Feio et al, 2016; Rinaldi et al., 2017).

Still, Wohl et al. (2015) legitimately asked, “*How do we approach river restoration*?” A generalised and quantitative answer to that question is not yet available, especially from a technical point of view. In addition to the scientific underpinnings, decision makers require accountability of the lifespan of restoration features for prioritising particularly relevant projects. Society is spending a lot of money to build projects, but too little effort has gone into ascertaining the longevity of such investments.

This study uses a large dataset from California’s well-documented lower Yuba River (e.g., Barker et al., 2018; Pasternack and Wyrick, 2017) to create lifespan maps for quantifying the lifetime of stream restoration features. The term "feature" denotes any one specific technical component to achieve some beneficial stream restoration on a reach scale (10 to 100 times the channel width, Pasternack and Wyrick, 2017). An example of a feature is "vegetation planting" to improve habitat quality and increase channel stability.

A comprehensive and interdisciplinary literature review identifies relevant features and the fundamental data necessary for assessing their lifespans. Moreover, the literature review identifies parameter-related survival thresholds, where constructive details are listed in the supplemental material. Based on the parameter thresholds, we introduce a procedure for deriving lifespan maps and then test that approach using a proposed habitat enhancement framework for the lower Yuba River.

2. Methodology

2.1. Approach

Wohl et al. (2015) identify ten common goals of river restoration on several scales, which are achieved by applying stream restoration features. We consider only constructive features without taking into account requirements such as “land acquisition”. Moreover, we exclude “dam removal” because of the complexity and involvement of factors that cannot be assessed with hydrodynamic modelling and topographic change measurements (O’Connor et al., 2015; Foley et al., 2017). For example, dams often have multiple purposes (e.g., flood protection, hydropower generation or water supply) and they may be required for resilience and security of water resources as well as energy generation (Beatty et al., 2017; Schleiss, 2017). Therefore, dam removal or discharge releases imply higher order administrative decisions (Grant, 2001; Tullos et al., 2016; Stamou et al., 2018) beyond the scope of reach-scale stream restoration. However, we consider the removal of small structures such as sills, check dams (closed type) or bank reinforcements in the review of reach-scale restoration features.

Table 1 lists restoration goals (Wohl et al., 2015) that can be achieved with numerically assessable features at the river reach scale. Relevant features (indicated with “x”) can potentially be numerically characterised by topographic change and hydrodynamic modelling. The listed features result from a review of habitat enhancement projects that are mainly situated in the United States (see the supplemental material for a complete list). Projects that are briefly mentioned in the literature without indication of technical details of features served for the verification of the completeness of the feature list. Moreover, this study does not consider passive actions or features that are restricted to a single project, including human employment.

The following sections introduce the study site of the lower Yuba River, parameters characterising the physical stability of features and a review of the relevant features (Table 1) with explanations of their application. The review leads to the identification of quantitative hydraulic and geomorphic parameters controlling lifespan. These parameters have threshold values. When flood flows exceed the feature-specific thresholds, the related features become physically unstable which represents termination of their lifespan. Relating parameter threshold values to flood return periods (i.e., recurrence intervals) enables estimation of a feature’s expected lifespan. Finally, we provide explanations on the creation of maps indicating the resulting lifespans of proposed restoration and habitat enhancement features for the lower Yuba River.

2.2. Study site

The Yuba River is located in Northern California. Its lower 37-km segment is being evaluated for diverse river restoration projects supporting anadromous spring-run Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*O. mykiss*), both federally listed as threatened species. This wandering cobble-gravel bed river has coarse substrate (0.30 m) at Englebright Dam where the segment begins and much finer substrate (0.04 m) close to its confluence with the Feather River (downstream boundary) ment (Jackson et al., 2013). The average wetted baseflow width is 59.4 m and the average channel slope varies between 0.16 and 0.18%. Irrigation water (approximately 9.9 m^3/s) is diverted at Daguerre Point Dam located 17.8 km upstream of the Feather River .

Table 1: Stream restoration features and their primary goals (Bernhardt et al., 2005; Wohl et al., 2015), which are marked with "x".

Features	Bank & channel stabilisation	Channel reconfiguration	Floodplain connectivity	Instream habitat recovery	Recreation, Aesthetics	Fish passage	Flow modification	Species management
Bar & Floodplain grading			x					x
Berm setback (widening)	(x)	x	x	(x)	x			x
Plantings	x		x	x	x			x
Riprap	x	x		x				
Sediment replenishment	x	x	x	x				
Side cavities[1]	x			x	x			x
Side channels	(x)	x	x	x	x			
Structure removal[2]		x	x	x	x	x		
Swale and backwater creation		x	x	x	x			x
Wood[3]	x	x		x				

[1] Includes groynes and bank scalloping

[2] Sills, check dams, bank reinforcements

[3] Refers to engineered log jams and rootstocks

Several morphologically important discharges have been determined for the lower Yuba River (Abu-Aly et al., 2014). Englebright Dam controls flows below 118.9 m^3/s. An environmental flow regime is in place with seasonally variable releases depending on a water-year classification. In normal to wet years, 25 m^3/s is a typical baseflow discharge. Based on thorough geomorphic investigation, the bankfull discharge corresponds to a 1.2–year flow recurrence interval of 141.6 m^3/s. Other relevant flows include the floodplain inundation flow (2.5–year return flow of 597.5 m^3/s), double the floodplain inundation flow (a 4.7–year return flow of 1195 m^3/s), quadruple the floodplain inundation flow (12.7–year return flow of 2390 m^3/s) and the peak flood associated with the 2006-2008 topographic map (a 20.0–year recurrence interval flood of 3126 m^3/s).

2.3. Pre-existing data used in this study

The lower Yuba River has been a testbed river segment for a variety of basic and applied hydrodynamic, geomorphic, and ecohydraulic research topics for the last 15 years, yielding abundant baseline data and hydrodynamic models vetted through independent scientific peer reviewed journal procedures and locally driven open review by stakeholders (e.g., government agencies, private industry, and non-governmental organisations). The lifespan maps reported in this study build upon those existing datasets and, therefore, this article does not extensively reiterate their development.

The four primary sources of inputs to the lifespan maps consist of stream gage records, a riverbed sediment facies survey, repeated topographic surveys of the river, and a set of 2D hydrodynamic models of the river. Past literature detailing the maps and models is publicly available (Jackson et al., 2013; Abu-Aly et al., 2014; Pasternack and Wyrick, 2017). Flow data used in this study was obtained from the United States Geological Survey (USGS) stream gages that are located downstream of Englebright Dam at Smartsville (#11418000) and at Marysville (#11421000).

Given the large area of the lower Yuba River, the best way to characterise riverbed sediments for the bankfull channel involved visual facies mapping that identifies the surface pattern by classifying patches of similar grain size distributions. For each patch, a specifically trained research crew estimated the relative abundance of seven size bins (see Table A.II, supplemental material) to the nearest 10%. The training consisted in visually estimating grain size classes of known sediment samples. Size bins were designed to maximise visual difference given the specific size distribution of surface substrate particulars in the lower Yuba River (Jackson et al., 2013). Observer testing affirmed the high quality of crew performance in both properly identifying presence/absence of each class, as well as estimating their abundances. From these data, multiple rasters mapping the spatial pattern of each size class were used to produce a single weighted-mean grain size raster. For the terrain outside of the bankfull channel, each raster pixel was identified as either vegetated or unvegetated. Both types were assigned the weighted mean grain size of the ground type from the bank region (i.e., between perennial baseflow and the bankfull bank top).

Topographic surveys used in this study were conducted during 2008 and 2014. The 2008 surveys cover the whole river, except for one remote, dangerous, narrow 2.0-km gorge in the Englebright Dam Reach of the lower Yuba River (Weber and Pasternack, 2017). The topographic surveys were used to produce digital elevation models (DEMs) with 1x1 m^2 pixels.

A number of derivative data products were generated from DEMs and 2D models as part of past research, and are used as the primary inputs for producing the lifespan maps. Topographic change detection and analysis is an emerging essential tool for geomorphic research, including understanding the longevity of existing landforms (Wheaton et al., 2010). This study used the pre-existing DEM of difference from 2008-2014, which accounts for uncertainty using a fixed minimum level of detection threshold, plus a spatially varying statistical level of detection threshold, as rigorously determined and explained in Weber and Pasternack (2017). In this study, the DEM of difference was used to identify average scour and fill rates that are, e.g., relevant for the survival of plantings.

Meter-resolution, two-dimensional hydrodynamic (2D) models were developed with the United States Bureau of Reclamation SRH-2D algorithm from the 2008 DEM. Models span the whole river, except the narrow gorge, and simulated 28 steady state flows ranging from 8.50 to 3126 m^3/s (Barker et al., 2018). Model results include rasters of water surface elevation, flow depth h, depth-averaged flow velocity u and energy slope S_e.

From these model outputs, a number of derived products were created, including a depth-to-groundwater raster, a bed shear stress raster, the largest discharge-dependent representative mobile grain size, and a spatially explicit landform map. The depth-to-groundwater raster was produced by projecting the water surface elevation map for the typical baseflow discharge of 25 m³/s out under the terrain DEM and subtracting it from the terrain DEM.

Discharge-dependent and spatially variable grain mobility was predicted as a function of the dimensionless bed shear stress τ_*(Du Boys, 1879; Von Karmàn, 1930; Kramer, 1932). Grains can be expected to be mobilised when the dimensionless bed shear stress exceeds a threshold value of grain mobility $\tau_{*,cr}$ equal to 0.047 (Lamb et al., 2008; Shields, 1936). In gravel-bed rivers with a logarithmic vertical velocity profile (e.g., Pasternack et al., 2006), the dimensionless bed shear stress can be computed from the following equation (Keulegan, 1938; Einstein, 1950):

$$\tau_* = \frac{1}{D_{84}\, g\, (s-1)} \left[\frac{u}{5.75\, \log_{10}\left(12.2\, h/(2\, D_{84})\right)}\right]^2 \qquad (1)$$

The variable D_{84} corresponds to the bed grain size at which 84% of the bed sediment is finer. It appears here as the relevant grain size for roughness (Rickenmann and Recking, 2011); g denotes gravitational acceleration; s is the ratio of the sediment and water densities that typically takes values of 2.6 to 2.7 (e.g., Rickenmann, 1990). Surface weighted-mean grain size estimates from Jackson et al. (2013) multiplied with 2.2 are used in this study for deriving D_{84} (according to Rickenmann and Recking, 2011).

2D model outputs, notably, the flow depth h and the energy slope S_e provide estimates of the largest discharge-dependent representative mobile grain size based on:

$$D_{mobile,i} = h_i \cdot S_{e,i} / \left[(s-1)\, \tau_{*,cr}\right] \qquad (2)$$

The variables h_i and $S_{e,i}$ are the flow depth and energy slope related to a flood discharge i according to the flood return periods that are being considered.

Pasternack and Wyrick (2017) mapped the in-channel morphological units for the lower Yuba River. Overbank morphological units (floodplains, hillsides and terraces) resulted from an expert assessment. These morphological units limit the application of restoration and habitat enhancement features to reasonable locations. For example, berm setback only makes sense where berms or similar structures are present. The supplemental material contains a complete list of morphological units that were considered.

The subsequent literature review aims at revealing threshold values of the above-described parameters for assessing feature stability.

2.4. Relevant stream restoration features

2.4.1. Bar and floodplain grading

Bars and floodplains that are disconnected from the aquatic ecosystem are candidates for terrain lowering and terracing (grading), respectively. A disconnection may occur because of channel incision, when the sediment transport (supply) is insufficient to sustain (maintain) the bed level, or because of sediment deposition when the sediment supply exceeds the local transport capacity (Jaeggi, 1984; Chang, 1985; Lisle et al., 1993). Streams may experience insufficient sediment supply because of dams or excess sediment supply because of mining (e.g., Gilbert, 1917).

In the case of sediment scarcity, grading of disconnected bars and terracing of floodplains is reasonable in combination with sediment replenishment or plantings. In particular, vegetation plantings require a short distance to the groundwater table, which determines the extent of grading (required lowering level), especially in arid climates. Numerical model simulations help to identify bars and floodplains that are rarely flooded.

Thus, the distance to the groundwater table combined with the inundation frequency determine candidate sites for grading. Potentially disconnected bars and floodplains can be identify by expert assessment of morphological units (e.g., Pasternack and Wyrick, 2017). The supplemental material contains more details on the effects of terrain lowering on the channel morphology.

2.4.2. Berm setback and river widening

Existing artificial (i.e., man-made) lateral channel confinements such as berms and dykes can be back-shifted in uninhabited areas. Such setbacks create a widened river section to increase flow passage capacity and decrease sediment transport capacity for each stage impacted by the widening. Widened river sections have more room for lateral habitat abundance and heterogeneity. Moreover, water quality improves and the longitudinal profile stabilises. All of these changes benefit aquatic organisms and riparian vegetation (Reichert et al., 2007; Weber et al., 2009; Woolsey et al., 2007). River widening additionally creates recreation areas (Bernhardt et al., 2005, 2007). Newly created splays are also an opportunity for establishing habitat enhancing side channel systems.

Consequently, berm setback and river widening are adequate features for stream restoration as long as there is no interference with existing infrastructure and flood safety. An expert assessment of morphological units (e.g., Pasternack and Wyrick, 2017) helps to identify lateral structures that are suitable for berm setback. The supplemental material contains additional information on the long-term effects of berm setback.

2.4.3. Planting of vegetation

Plants have habitat enhancing and stabilising effects on the riverbanks and floodplains. In addition, indigenous riparian vegetation provides and improves habitat because it has multiple functions such as filtering, shading, cover, and nutrient provision (e.g., Naiman and Décamps, 1997; Vehanen et al., 2000).

Complementary bioengineering techniques such as geotextiles or wattle fences protect the soil from scouring and increase the survival of plantings. Moreover, engineered logjams produce a wake that protects young plantings and increases their survivorship, particularly on gravel bars (Edwards et al., 1999; Vesipa et al., 2017) and/or with the support of native indigenous shrubs (e.g., Castro et al., 2006).

The survival of plantings depends on dimensionless bed shear stress (Friedman and Auble, 1999), sediment scour or deposition rates (Bywater-Reyes et al., 2015; Kui and Stella, 2016; Pasquale et al., 2014), flow submergence and velocity (Friedman and Auble, 1999; Vesipa et al., 2017), and particularly in arid regions, the distance to the groundwater table (Politti et al., 2018).

Plants generally increase the roughness and decelerate the flow (Abu-Aly et al., 2014; Järvelä, 2002, Ricardo, 2014) leading to higher flow depths. This results in a circular relationship between plants and hydraulic forces (e.g., Wilcox and Shafroth, 2013), which requires particular attention to ensure flood safety in populated areas. The hydraulic effects of plants decrease with decreasing leaf and plant size, stem density and sediment supply. A deficient sediment budget dampens the hydraulic effects of plants (Manners et al., 2015).

A list of country-specific databases is included in the supplemental material. In this study, we used the Calflora (2017) database and reports from local sources (SYRCL, 2013; USACE and YCWA, 2016) to identify the following indigenous species in the Northern Californian foothills, where the lower Yuba River is located: Cottonwood (*Populus fremontii*), Willows (*Salix gooddingii*, *Salix laevigata* and *Salix lasiolepis*), White Alder (*Alnus rhombifolia*) and Box Elder (*Acer negundo*). Although more indigenous species exist, we limited the analysis to those for which numeric survival criteria are available. For the lifespan maps, Table 2 lists the survival criteria for the four plant genera that were considered. The supplemental material contains details on the studies considered, but the available data on plant stability is limited, and more studies on other plant species and older plantings are desirable in the planning of stream restoration.

2.4.4. Riprap, rocks and boulders

The punctual placing of boulders (at a specific point in space) or comprehensive block cover apply to unstable banks or erosion-prone surfaces. The boulders and blocks are sometimes referred to as “riprap” with different sizes (diameters) and they reduce hydrodynamic forces on the flow boundaries (banks and channel bed). Riprap locally creates additional near-bed turbulence, which stabilises the bed and enhances habitat.

The application of riprap ranges from bank revetment and bed or toe protection to the construction of dikes and groynes, and vegetation may be incorporated. When riprap is damaged, it can be easily repaired if done promptly (Maynord and Neill, 2008).

Common failure mechanisms are the direct erosion of blocks, translational slides on steep banks, modified slumps in riprap when toe support is missing or the erosion of supporting slopes after bank overtopping (Julien, 2002). An adequate technique for riprap placing and sizing prevents such failures, where several approaches for the assessment of the adequate riprap size exist. Such design concepts result from a balance of tractive forces (Maynord and Neill, 2008) or probabilistic assessments of block density and weight (Li et al., 1976). Stevens et al. (1976) or USACE (1994) proposed popular approaches for the sizing riprap. These methods refer to 1D cross-section-averaged flow depth and velocities. The 2D models of the lower Yuba River enable an alternative assessment of required block diameters. Thus, relevant riprap sizes are estimated based on the evaluation of the 2D models for Eq. (2.). The supplemental material explains the alternative application of the 1D formulae from Stevens et al. (1976) or USACE (1994).

2.4.5. Sediment replenishment (Gravel augmentation)

Dams block coarse sediment flux from the catchment, which leads to the morphological depletion of downstream reaches. In these cases, the restoration of sediment transport dynamics by sediment injections, also referred to as gravel augmentation or sediment replenishment (Battisacco et al., 2016; Bunte, 2004; Kondolf 1997; Pasternack et al., 2010), is crucial for the eco-morphological river state (e.g.,

Table 2: Survival parameters of the Populus, Salix, Alnus and Populus genera.

Genus	Parameter		Source
Name *(Latin)*	Name	Threshold	Author (year)
Cottonwood *(Populus)*	Burial (sediment deposition)	< 0.8 times seedling length	Kui and Stella (2016); Polzin and Rood (2006)
	Scour (sediment erosion)	< 0.2 times root depth	Kui and Stella (2016)
		< 0.5 times root depth	Bywater-Reyes et al. (2015)
		< 0.1 times root depth	Polzin and Rood (2006)
	Flow velocity	1 to 1.25 m/s	Bywater-Reyes et al. (2015); Stromberg et al. (1993); Wilcox and Shafroth (2013)
	Flow submergence	< 0.5 times stem height	Stromberg et al. (1993)
	Depth to groundwater	min. 1.5 m, max. 3.0 m	Politti et al. (2018); Polzin and Rood (2006); Stillwater Sciences (2006)
Willow (*Salix*)	Submergence (shrub protrusion above water)	> 0.1 m	Pasquale et al. (2014) Pasquale et al. (2012) Pasquale et al. (2011)
	Dimensionless bed shear stress[1]	$\tau_* < 0.1$	
	Scour depth	< 0.1 times root depth	
	Depth to groundwater	min. 1.0 m,	Stillwater Sciences (2006);
		max. 1.5 m	Politti et al. (2018)
Alder (*Alnus*)	Scour depth	< 0.3 m per year	Jablkowski et al. (2017)
	Depth to groundwater	min. 0.3 m, max. 1.5 m	Stillwater Sciences (2006)
Box elder (*Acer negundo*)	Burial	Survives any depth	Kui and Stella (2016)
	Dimensionless bed shear stress	$\tau_* < \tau_{*,cr}$	Friedman and Auble (1999)
	Submergence duration	< 85 days per year	
	Depth to groundwater	min. 1.0 m, max. 2.0 m	Stillwater Sciences (2006)

[1] *Given a root depth of >0.5 m and a stem height >1.0 m.*

Hassan et al., 2005). Post-injection analyses have reported on the benefits of well-designed injection programs (Bunte, 2004; McManamay et al., 2011).

The adequate choice of the grain size for sediment replenishment requires the differentiation of two different bedload transport modes (Piton and Recking, 2017): (1) travelling bedload and (2) structural bedload. Travelling bedload transits the river section and it deposits on the riverbanks during floods. Thus, overbank deposits created by floods indicate the size of travelling bedload. The sources of travelling bedload are channel-extern, i.e., fine material from the upstream catchment area or lateral slope erosion. Habitat enhancement preferably considers the size of structural bedload corresponding to the channel bed grain diameter for channel maintenance and spawning substrate replenishment.

Ock et al. (2013) propose four different possibilities for placing gravel in rivers:

- In-channel stockpiles of sediment;
- High-flow stockpiles on the floodplain;
- Point bar stockpiles on the floodplain and river banks;
- High-flow direct injections with conveyor belts.

In-channel gravel injections instantaneously create spawning habitat. Out-of-channel stockpiles should be movable by morphologically effective floods.

Thus, relevant parameters for lifespan maps are the present surface grain size related to the mobile grain size according to Eq. (2). The interpretation will require a differentiated consideration of suitable locations for in-channel gravel injections, which are located in areas of low grain mobilisation rates, and out-of-channel stockpiles, which need to be movable by the small frequent floods close to the bankfull discharge.

The ample literature on sediment replenishment is summarised in the supplemental material and indicates technical details regarding adequate locations, stockpile geometry, discharge conditions, morphological effects, grain size and sediment volumes.

2.4.6. Side cavities (bank scalloping and groynes)

Side cavities are also referred to as “embayments”, “macro roughness” or “Wandos” (in Japan) in the literature (Juez et al., 2017; Nezu and Onitsuka, 2002; Uno et al., 2013). In-river reaches with monotonous banks and in the absence of roughness elements, artificial side cavities produce valuable habitat. Side cavities serve aquatic species by providing refugia and cover from predators. Alternatively, side cavities can help stabilise bank toes.

Two types of features create side cavities: (1) punctual extensions of the banks with groynes and (2) excavation of embayments in the banks; both create habitat-favourable, variable flow fields with low and high velocities (McCoy et al., 2008).

Groynes are characterised by large cavity widths W compared with the channel width w and short cavity interspaces l. Embayments typically have long cavity interspaces l compared with the cavity length L (cf. Fig. 1 and Juez et al., 2017). These parameters are important for estimating the probability of sedimentation of artificial side cavities (see trends in Fig. 3), where fine sediment is desired as a nutrient source (e.g., Kollongei and Lorentz, 2014) but it may cause undesired clogging of the streambed resulting in the deterioration of spawning habitat (Kondolf 1997; Sternecker et al., 2013). The supplemental material summarises design criteria for limiting cavity sedimentation by provoking transversal oscillations, similar to lake seiches, which favour the re-suspension of fine sediment in embayments (Rockwell and Naudascher, 1978; Meile et al., 2011; Juez et al., 2017).

The lifespan maps consider side cavities as an on/off criterion because adequate sites for side cavity creation are only delineated by the morphological units “bank”, “cutbank”, “lateral bar” and “spur dike”, where the annual fill rate is smaller than 0.3 m to avoid cavity sedimentation. The supplemental material contains constructive details from the comprehensive literature.

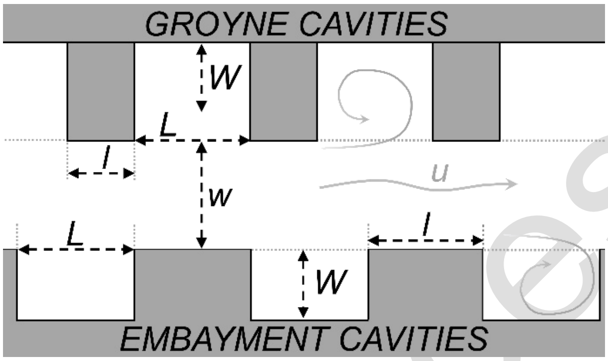

Figure 1: Two types of side cavities: groynes and embayments (based on Juez et al., 2017); with indication of the main channel width w, cavity width W, cavity length L and interspace l, as well as qualitative flow vectors.

2.4.7. Side channels and anabranches

Anabranching rivers are interesting for river restoration because they provide valuable and sustainable habitat (Riquier et al., 2017). Such multiple thread channels are categorised into stable anabranches (also: anastomosing channels, cf. Nanson and Knighton, 1996; Schumm, 1985), semi-permanent wandering gravel-bed channels (Church, 1983) and fast changing braided channels (Leopold and Wolman, 1957). Many factors are believed to contribute to the formation and stability of anabranches. There is consensus that the balance between the sediment transport capacity and sediment supply, as well as the bank stability, determine the dynamic equilibrium between side and main channels (Cittero and Piégay, 2009; Huang and Nanson, 2007; Lane, 1955; Leopold and Wolman, 1957; Kleinhans et al., 2008; Nanson and Knighton, 1996). The dynamic equilibrium imposes a superordinate morphological planform, which is conditionally stable but hard to achieve through anthropological river design in a complex system of variable (flood) discharge and sediment supply (e.g., Bliem et al., 2012; Bolla Pittaluga et al., 2003; Eaton et al., 2004; Formann et al., 2014). The supplemental material contains further information on dynamic equilibrium.

Candidate sites for creating anabranches are located in wide, shallow splays and downstream of river bends where stable banks are a fundamental requirement for anabranch longevity (Huang and Nanson, 2007; van Denderen, 2017).

Unstable channel banks facilitate avulsion, which is typical for semi-permanent wandering gravel-bed channels (Church, 1983). Cohesive sediment, rock and vegetation increase bank stability (Eaton et al., 2004), which favours longevity of side channels (Makaske et al., 2009; Nanson and Knighton, 1996; van Denderen et al., 2017). Moreover, the stability of artificial side channels significantly depends on the partitioning of discharge and sediment between the main and side channels. Partitioning is controlled by bend flow effects, bifurcation angle (between the main and side channel axes), and transverse bed slope, as well as the relative lengths of the main and side channels (Bolla Pittaluga et al., 2015; Dutta et al., 2017; Kleinhans et al., 2008).

The design of side channels can be enhanced with stabilising elements such as riprap or plantings combined with bioengineering features. However, the current state of the science is insufficient to derive numeric parameters for lifespan maps.

2.4.8. Streambed reshaping

Depressions in the terrain beside the main channel, which experience only minor morphological work from floods, are potential candidates for the creation of swales, slack- and backwater zones. These features aim at habitat enhancement through the creation of calm water zones at baseflow conditions (Bolton and Shellberg, 2001).

Potential sites for calm water zone creation are characterised by low dimensionless bed shear stress with small terrain fill or scour rates and particular morphological units besides the main channel. Thus, a limit of 0.03 m per year for the annual scour or fill rates applies and relevant morphological units are “agriplain”, “backswamp”, “mining pit”, “pond”, “pool”, “slackwater” or “swale”.

2.4.9. Structure removal / replacement

The eco-morphological state of many rivers is impacted by transversal structures such as (check) dams (Comiti, 2012) or groundsills (Weitbrecht et al., 2017). Ineffective (open) check dams for sediment retention in the case of floods may be removed or replaced by more effective structures with less impact on the longitudinal river connectivity (Schwindt et al., 2018). Transversal barriers (i.e., groundsills and close-type check dams), originally for channel bed stabilisation (Piton et al., 2017), can be replaced by structured or unstructured block ramps (following the suggestions from Weitbrecht et al., 2017). Structured block ramps (artificial step-pool systems) can be used for channel slopes up to 7%, while unstructured block ramps, which are favourable regarding the hydrodynamic habitat suitability, are applicable at slopes of maximum 1 to 3% (Janisch et al., 2007; Schleiss and Studer, 2016; Weitbrecht et al., 2017).

The removal of lateral structures such as dykes, berms or bank reinforcements enhances the lateral habitat connectivity. These actions correspond to river widening, as described in the framework of *berm setback*.

Unnatural angular rocks or blocks, including rock fragments blasted during construction of hydraulic structures, may injure spawning salmon and steelhead that build redds and bury their eggs in the streambed. Results presented in Pasternack et al. (2010) suggest that “shot-rock” removal should only be undertaken if it is combined with large-scale gravel placement and spawning habitat rehabilitation. Although such sharp-edged unnatural rocks are inadequate spawning substrate, they constitute additional friction (roughness) that slows down the flow and contributes to channel stability. For this reason, several authors advise that angular blocks (“shot-rock”) should not be removed (e.g., Beschta, 1979; Beschta and Jackson, 1979; Burns, 1970) and adequate spawning substrate is better achieved through sediment replenishment.

No parameters for quantifying the utility of structure removal are identifiable for the lifespan maps and every removal-candidate requires a differentiated consideration.

2.4.10. Wood placement

Instream wood provides valuable habitat (e.g., Nagayama et al., 2012) and enhances sediment storage (e.g., Gallisdorfer et al., 2016). Two placement methods are distinguished, notably the placement of unsecured large woody material and the installation of (anchored) engineered logjams (e.g., Manners et al., 2007). Streams, where habitat enhancement with large woody material is reasonable, are characterised as follows (NRCS, 2001):

- Low to moderate entrenchment (ratios $>$ 1.4, cf. Rosgen, 1994);
- Low ratios between bank height and bankfull flow depth ($<$ 1.2, cf. Rosgen, 1994);
- Moderately steep channel slopes (0.1% to 4%);
- Coarse sediment (rock, boulders, cobbles and gravel);
- Riffle-pool (e.g., Lisle, 1979) and plane bed channels (e.g., Montgomery and Buffington, 1997).

In addition, cascade, step-pool or plane bed morphologies (e.g., Montgomery and Buffington, 1997) and moderately steep channels with sandy to silty sediment are marginally suitable for unsecured large woody material introduction. Highly entrenched streams or (artificial) multiple thread or anastomosed (side) channel systems can be subjected to local logjams that are caused by mobilised logs during floods (Ruiz-Villanueva et al., 2014). Such logjams are a problem (e.g., at bridges and culverts), where they can cause flooding. Hence, streams with the following characteristics are not suitable for large wood placement (NRCS, 2001):

- High entrenchment (ratios $<$ 1.4);
- High ratios between bank height and bankfull flow depth ($>$ 1.4);
- Multiple thread channels (cf. side channels, which may close because of jams).

During floods, loose pieces of large wood can cause serious damage at downstream structures (e.g., logjams can occur immediately upstream of bridges and prevent accumulated debris from moving downstream), which makes expensive protection measures necessary (e.g., Piton and Recking 2016). The mobilisation of loose logs is a function of flow depth, wood diameter D_w and/or Froude number. Thus, wood is entrained when (Braudrick and Grant, 2000; Lange and Bezzola, 2006):

- Flow depth is more than 1.7 times log diameter;
- Froude number exceeds values of 1.0 to 1.25.

Ruiz-Villanueva et al. (2016) estimated the probability of wood transport corresponding to -0.18 D_w/h + 0.32 in single thread and -0.49 D_w/h + 0.58 multiple-thread channels. Numerical models of wood transport (e.g., Ruiz-Villanueva et al., 2014) may increase the prediction of wood mobilisation and flow paths. The risk of unwanted logjams means that loose wood features are not adequate for stream restoration. Alternative biotechnical features such as rootstocks or engineered logjams provide similar or even better fish habitat and increased stability.

Addy and Wilkinson (2016) highlight that the implementation of engineered logjams requires the careful consideration of hydrodynamics to ensure stability (see also Bennett et al., 2015). In their experiments, Addy and Wilkinson (2016) conclude that only 4 out of 33 engineered logjams functioned as desired and only about 50% caused a geomorphic response. Three of their engineered logjams experienced toe scour and were damaged.

The construction of engineered logjams is not only about counterbalancing tractive hydrodynamic forces, but also about adequate placement in the channel, on banks or on the floodplain to ensure sufficient submergence depths and durations for providing fish habitat from wood (e.g., Brooks et al., 2004).

The lifespan maps highlight potentially suitable sites for wood placement based on the Froude number and the flow depth related to a log diameter of 0.6 m (USACE and YCWA, 2016).

2.4.11. Cross-application of features and soil bioengineering

Many features amplify their habitat enhancing effects in combination with other features. Table 3 indicates compatibilities among complementary features, according to the descriptions in the literature review, where side cavities are differentiated between bank embayments and groynes. The application can be further improved through bioengineering techniques, which prefer locally available, organic and inorganic construction materials (Gattie et al., 2003; Stiles, 1988). The supplemental material lists complementary bioengineering techniques with links to the features that were considered.

Table 3: Cross-links (marked with "x") of features.

Complementary features	Bank embayment [1]	Bar & floodplain grading	Berm setback	Engineered log jams (wood)	Groynes [1]	Plantings (var.)	Riprap	Sediment replenish.	Side channel creation	Structure removal	Swale and backwater creation
Bank embayment [1]	-			x	x	x	x				
Bar & floodplain grading		-	x			x		x			x
Berm setback (widen)		x	-			x			x	x	x
Engineered log jams (wood)	x			-	x	x	x				
Groynes [1]	x			x	-	x	x		x	x	x
Plantings (var.)	x	x	x	x	x	-	x		x	x	x
Riprap	x			x	x	x	-		x	x	x
Sediment replenish.		x						-			x
Side channel creation			x		x	x	x		-	x	x
Structure removal			x		x	x	x		x	-	x
Swale and backwater		x	x	x	x	x	x	x	x	x	-

[1] Embayments and groynes constitute side cavities

2.5. Concept of lifespan maps in restoration planning

The literature review of restoration features identified numeric hydro-morphodynamic stability criteria with threshold values for determining the feature longevity. Table 4 summarises applicable parameters and states threshold values for every feature considered, where associated morphological units are not explicitly repeated in the table. Some features lack numerically quantifiable hydro-morphodynamic stability criteria, and therefore, lifespan maps cannot be developed for side channels or structural removal.

The particular threshold values compared with discharge-dependent values from the numerical 2D hydrodynamic models indicate the survival of features on maps. The modelled discharges correspond to flood return periods of 1.2, 2.5, 4.7, 12.7 and 20.0 years, which serve for estimating the feature lifespan. The values for restoration feature stability thresholds were compared against 2D modelling derived rasters of the lower Yuba River at each test discharge using GIS software (ESRI, 2017 or QGIS, 2018). Such comparisons spatially indicate where survival thresholds of a particular feature are exceeded. In some cases, multiple parameters determine the feature lifespan, which requires the combination of several lifespan maps to determine the optimum location of a feature.

Table 4: Threshold values applied for determining feature stability, where "na" means "not applicable".

Feature (name)	**Depth to water** (m)	**Shear stress** (--)	**Fill** (m/year)	**Flow depth** (m)	**Flow velocity** (m/s)	**Froude number** (--)	**Morph. unit** (string)	**Scour** (m/year)
Bar & floodplain grading	2 - 4	0.047	na	na	na	na	yes	0.03
Berm setback	6 - 23	na	na	na	na	na	yes	na
Plants: Box Elder [1]	1 - 2	0.047	na	0.2·2	na	na	na	na
Plants: Cottonwood [1]	1.5 - 3	na	0.8·0.2·2	1.5·0.2·2	1	na	na	0.1·0.8·2
Plants: White Alder [1]	0.5 - 1.5	0.047	na	na	na	na	na	0.3
Plants: Willow [1]	1 - 1.5	0.1	na	0.2·2+0.1	na	na	na	0.1·0.8·2
Riprap	na	0.047	na	na	na	na	na	0.3
Sediment replenishment	na	0.047	na	na	na	na	na	na
Side cavities	na	na	0.3	na	na	na	yes	na
Side channels	generally not applicable							
Structure removal	generally not applicable							
Swale and backwater	na	0.047	0.03	na	0.03	na	yes	0.03
Wood	na	na	na	1.7·0.6	na	1	yes	na

[1] Hypotheses: Minimum stem height = 2 m, Planting depth = 80% of stem height

Figure 2 exemplarily illustrates the procedure for obtaining lifespan maps based on the discharge-dependent grain mobility D_{mobile} (Eq. 2) compared with the current state (grain size according to Jackson et al., 2013). The D_{mobile}-maps result from applying Map Algebra tools (ESRI, 2017) to the 2D model outputs of each of the considered flood discharges. The comparison of these maps with the present substrate grain sizes indicates the mobile surface related to the flood discharges. Merging these maps produces a hydraulic lifespan map, where the smallest discharge that mobilises grains is the limiting value. The amalgamation of multiple mobility frequency maps with rasters delineating the morphological applicability (scour/fill, morphological units) add the morphological component. Finally, the hydro-morphologic lifespan maps are matched with potential terrain confinements such as the depth to the groundwater table to produce what we denominate a “lifespan map” for every feature.

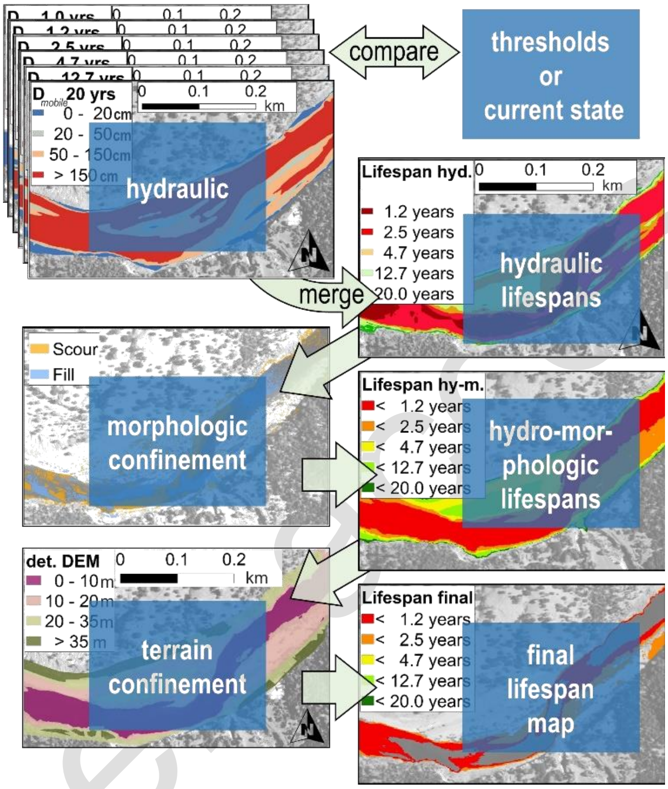

Figure 2: Procedure for creating lifespan maps: Exemplarily, the computed mobile grain size (Eq. 2) is vetted against the current state of present grain sizes to obtain hydraulic lifespan maps. Adding morphological parameters such as observed scour/fill rates and morphological unit delineation produce hydro-morphological lifespan maps. The final lifespan maps additionally includes terrain-related criteria such as the depth to groundwater table (important for plantings). Numbers in the figure are qualitative.

2.6. Habitat suitability and bioverification

The current state of habitat conditions in the lower Yuba River is quantitatively assessable as a function of preferable flow depths and flow velocities, which vary among species and growth stages (e.g., Ahmadi-Nedushan et al., 2006; Bovee, 1986). Fry often prefer shallower and low-velocity backwater areas, while juvenile fish may prefer deeper water and moving flows, as is the case for Chinook salmon (e.g., YCWA, 2013). The seasonal hydraulic preferences also vary among fish species, which requires the definition of environmental flows as a function of target species in the presence of dams (e.g., Stamou et al., 2018). The related species and growth-selective habitat suitability criteria (Bovee, 1986) enable the quantitative identification of the quality of discharge-dependent habitat (Gillenwater et al., 2006; Tiffan et al., 2002). The resulting habitat suitability index (CSI) indicates areas with high habitat suitability (CSI close to unity) and low habitat suitability (CSI close to zero). The supplemental material provides more details on the establishment and mapping of habitat suitability criteria.

The enhancement of habitat in the lower Yuba River primarily aims at increasing habitat for Chinook salmon and steelhead by applying the above-described features to regions where the habitat suitability index for all lifestages of Chinook salmon and steelhead is smaller than 0.4. The variation of CSI values with discharge is considered by super-positioning of CSI-rasters of multiple discharges with relevance to the reproduction of Chinook salmon and steelhead. These discharges vary between 8.5 m³/s and 141.6 m³/s. The supplemental material contains more information on the choice of discharges. Finally, we compare spatial CSI-rasters for Chinook salmon and steelhead with lifespan maps to identify where stream restoration makes sense not only ecologically but also economically.

3. Results

3.1. Lifespan maps

The application of the threshold values from Tab. 4 to the 2D hydrodynamic model output combined with the application of Eqs. (1) and (2), present grain sizes, the morphological unit and terrain confinement delineation leads to the lifespan maps shown in Fig. 3. These lifespan maps show the lower Yuba River’s Lower Gift Edge Bar between river kilometres 25.0 and 27.3. The lifespans are stated in years with the exemption of berm setback (Fig. 3b) and side cavities (Fig. 3g) delineation, which result from discharge-independent raster combinations.

Figure 3a shows the spatial lifespan estimates of bar and floodplain grading. These features make sense in locations where large floods with return periods of more than 12.7 years are insufficient to remodel the terrain. The lifespan estimates result from applying Eq. (1).

The lifespans of fresh Cottonwood plantings are shown in Fig. 3c. Box Elder, White Alder and Willows are mapped in the supplementary material. Once the cuttings established (i.e., having survived the first few years), their resistance against hydrodynamic forces, erosion and deposition increases. This conclusion is based on previous planting trials at Hammon Bar on the lower Yuba River (SYRCL, 2013) but to the Author’s best knowledge, there are no studies that quantitatively prove this observation. If Cottonwood plantings are well established after five years, Fig. 3c indicates that there would be adequate planting areas (shown in yellow and green) corresponding to lifespan estimates of more than 4.7 years.

Figure 3d indicates where riprap placement makes sense, as indicated by highlighting shear stress-intense regions (Eq. 1) combined with observed high scour rates. Thus, the lifespan map shown in Fig. 3d indicates that the outer bank of the sharp right bend of the lower Yuba River (bottom of the map) may require solid toe scour protection such as riprap. In addition, the stability of riparian vegetation plantings can be enhanced in regions where planting and riprap placement delineations intersect.

Swale and backwater creation in the main channel of the lower Yuba River have expectedly low lifespans (Fig. 3e). However, Fig. 3e indicates high longevity if the pond in the upper left edge would be connected to the main channel, thereby providing valuable backwater/swale habitat.

The lifespan map of sediment replenishment (Fig. 3f) requires a differentiated consideration: Gravel stockpiles for sediment replenishment placed alongside of the baseflow channel would be frequently

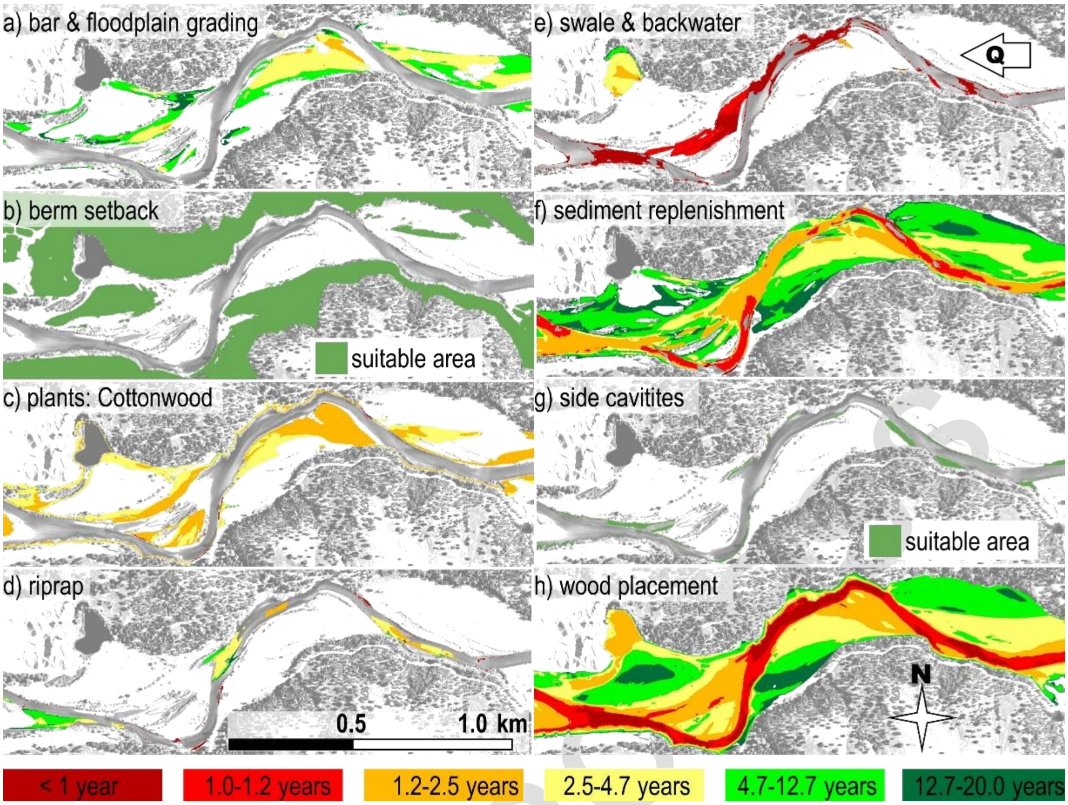

Figure 3: Lifespan maps for the considered stream restoration features at lower Yuba River's Lower Gift Edge Bar (river kilometre 25 to 27.3). The maps combine several parameters, notably, the flow velocity, flow depth, landscape fill/scour rates, the depth to groundwater and morphological unit delineation.

mobilised (i.e., nearly every year). Hence, the best locations for gravel stockpiles are in frequently mobile areas on bars, which are indicated by the orange surfaces in Fig. 3f. Gravel stockpiles beyond the main channel in the yellow to green regions of Fig. 3f are inefficient due to infrequent inundation and mobilization. In contrast to gravel stockpiles, relevant zones for gravel injections required yellow to green surfaces in the main channel. Thus, gravel injections in the main channel are not reasonable in the river reach displayed in Fig. 3f. A more suitable placement site for gravel injections in the main channel is located in the most upstream reach of the lower Yuba River, immediately downstream of Englebright Dam.

Adequate locations for wood placements in the shape of engineered logjams are indicated in Fig. 3h. This lifespan map highlights potentially suitable regions for wood placement, as illustrated in green.

The results from the lifespan maps (Fig. 3) indicate that the following restoration actions are reasonable habitat enhancements that could be implemented in the section of the lower Yuba River:

- Grading of surfaces indicated in (Fig. 3a), combined with plantings (supplemental material) and engineered logjams (Fig. 3h);
- Reuse of graded material for gravel stockpiles for (bi-) annual mobilisation on the lower floodplain (Fig. 3f);
- Riparian vegetation plantings combined with engineered logjams in relevant zones (Fig. 3c and supplemental material, superposed on Fig. 3h)

- Bank protection at the outer banks of the sharp left bend (red area in the top right of Fig. 3d) and the right bend (red area in the bottom centre of Fig. 3d) through groyne-cavities created with riprap, engineered logjams and plantings;
- Connection and enhancement of the pond in the upper left corner to integrate it as calm water habitat (Fig. 3e);
- Creation of side cavities (groynes and bank embayments) next to the unimproved road that is aligned parallel to the left bank of the river, as shown on the right-hand side of Fig. 3g.

3.2. Overlay of lifespan maps and habitat suitability index rasters.

The planning of ecological stream restoration projects often relies on areas where habitat suitability is low (Buijs, 2009). Lifespan maps are useful to investigate features that are also physically stable. Figure 4 exemplarily shows an overlay of low habitat suitability (CSI < 0.4) and lifespan maps of the grading feature. The area of low habitat suitability refers to the lowest CSI value of Chinook salmon spawning, fry and juvenile lifestages. The figure reveals that overlapping of ecologically relevant (CSI < 0.4) and physically reasonable (i.e., relatively sustainable between 4.7 and 20 years) application of grading is limited to a small fraction of the area. In order to identify the percentage of overlap, Fig 5 illustrates the ratio of areas of feature lifespans and the total area of low habitat suitability (CSI < 0.4).

A component of economic viability is introduced by dividing the sum of non-sustainable bars by the sum of sustainable bars in terms of expected lifespans as shown in Fig. 5. Thus, 19% of the ecologically reasonable grading area is not economically viable, if a lifetime of more than 10 years is desired (yellow bar divided by the sum of green bars in Fig. 5). Ecologically reasonable swale and backwater enhancements are up to 50% economically viable if a lifespan of more than 2.5 years is desired and only 85% are economically viable to achieve lifespans of more than 10 years. Thus, 85% of ecologically reasonable swale and backwater enhancement area can be excluded from restoration planning to improve the economic performance. Likewise, 94% of riprap, 68% of wood placement and 79% of plantings in the ecologically reasonable area can be excluded to achieve economical viability for 10 years.

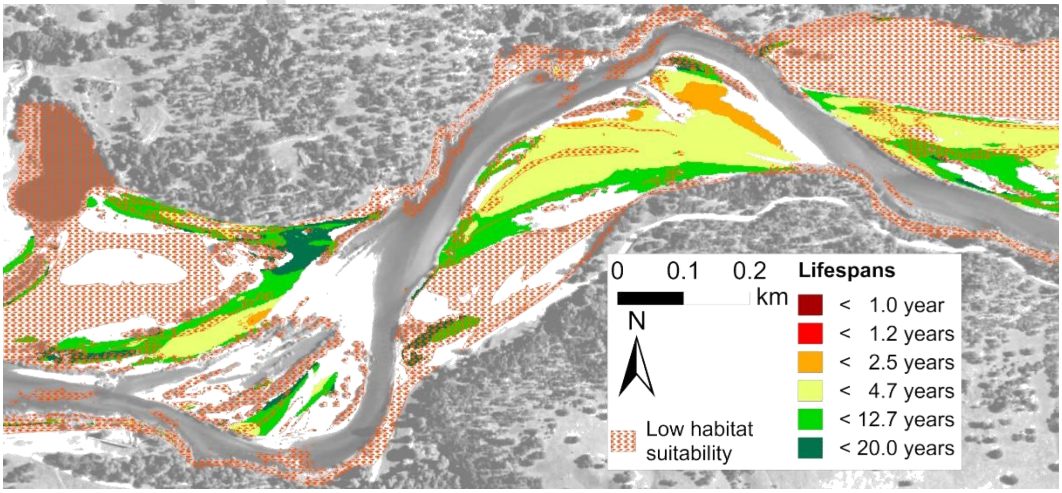

Figure 4: Overlay of low-habitat polygon (CSI < 0.4) with lifespan map of the grading-feature.

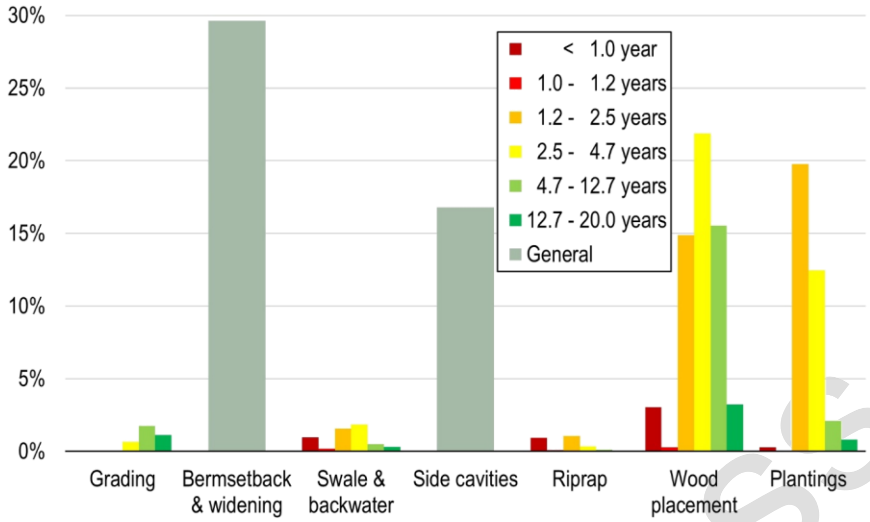

Figure 5: Relative applicable area of considered restoration features.

4. Discussion

4.1. Interpretation of lifespan maps

Beyond the estimated feature sustainability in years, lifespan maps indicate more generally, where the application of particular features could be put into practice successfully.

Landscape fill and scour maps can indicate disconnected zones that are omitted by morphological river activity, and therefore, these maps indicate where bar and floodplain grading is reasonable rather than indicating the lifespan of grading features.

Increasing the available habitat through berm setback (river widening) is generally beneficial for the morphodynamics and biodiversity (Reichert et al., 2007; Weber et al., 2009; Woolsey et al., 2007) but neither 2D hydrodynamic models nor DEMs of differences can predict the long-term evolution of widened river sections. Morphodynamic river models aim to predict terrain evolution and help evaluate the trajectory of restoration features like terrain grading or berm setback post implementation. However, the fully integrated coupling of sediment transport in hydraulic models is still in an early stage with challenges such as different velocities of water and transported sediment or the transition between the fix and mobile channel bed (Liu et al., 2015; Rosatti and Zugliani, 2015). Currently the approach applied here of coupling terrestrial scans and 2D hydrodynamic models for estimating the morphological evolution provides the most sophisticated tool, as also used in other studies of ephemeral stream morphology (Norman et al., 2017).

Sediment mobility maps that indicate mobile grain sizes for a particular restoration feature are an intermediate product of the lifespan map generation process based on Eq. (2). In the course of restoration planning, such mobile grain size maps can be reused for determining relevant grain sizes for gravel augmentation or riprap design once suitable sites are identified. For this purpose, there is one relevant discharge for which mobile grain size maps will always refer. For gravel stockpiles on the river banks that are desired to be moved downstream periodically within a timespan of management relevance to make stockpiling worthwhile, the single flow for which sediment mobilisation matters is bankfull discharge. On the lower Yuba River with mostly non-cohesive banks that is roughly the annual flood, and that is a good frequency for mobilising injected gravel.

By contrast, riprap needs to be stable at much higher floods, so that the required stable grain sizes refer to a high flood discharge. In the case of the lower Yuba River, the highest simulated discharge of 3126 m³/s multiplied with a safety factor of 1.3 applies for riprap. Figure 6 shows an example of minimum block sizes for riprap in a narrow 2.0-km gorge section of the Englebright Dam Reach of the lower Yuba River. According to Fig. 6, blocks of a diameter up to 5 m would be required in the centre of the channel to achieve stability. Thus, it is not surprising that the actual channel bed of the lower Yuba River in this gorge section is characterised by bedrock (e.g., Pasternack and Wyrick, 2017), which bears witness to the important tractive flow forces during floods. As a comparison, the Stevens et al. (1976) approach indicates that required riprap sizes of 0.9 m (using a cross-section-averaged velocity of 5 m/s, a channel bottom slope of 0.2% and a safety factor of 1.3, see computation script in the supplemental material). This comparison shows that 2D hydrodynamic models provide higher planning safety compared with 1D approaches, because they yield higher velocities in the fastest core of flow and lower velocities flanking instead of averaging across this natural variability.

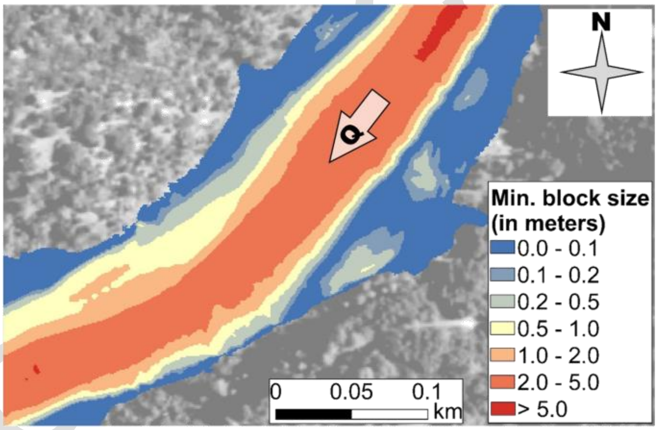

Figure 6: Mobile grain size maps based on a discharge of 3126 m³/s (multiplied with a safety factor of 1.3) for riprap downstream of Englebright dam at river kilometre 36.5.

Artificial swales or backwater directly in the streambed itself may be reversed or otherwise modified by morphologically active discharges, which can be associated to the bankfull or dominant discharge (cf. Williams, 1978; Wolman and Miller, 1960). The return period of morphologically effective discharges (floods) of natural rivers typically varies between 1 to 3 years in a temperate clime and in the absence of strong bed armouring, artificial bed reinforcement or bed rock (Crowder and Knapp, 2005; Hassan et al., 2014; Wohl, 2000). These numbers are confirmed by the lifespans of calm water zones in the main channel on Fig. 3e and other instream features (Fig. 3c, f and h). Thus, the return of investment of terrain reshaping at the baseflow level can be limited in morphologically dynamic streams, which is at the same time a benchmark of ecologically healthy streams (e.g., Moyle and Mount, 2007). Decelerated flow zones in the main river channel are preferably achieved through strategically placed punctual features such as engineered logjams or riprap. Also, side cavities (groynes or embayments) can sustainably create calm water zones. On the lower Yuba River, natural undulations in channel width, floodplain width, and valley width yield the same effect naturally in many places. Consequently, suitable sites for artificial backwater zones, swales or slackwaters are created besides the main river channel.

To assess side channel stability, Huang and Nanson (2007) use a classification scheme based on the comparison of the valley slope against the energy slope for determining the superordinate channel planform. Figure 7 documents the closure and reactivation of a side channel of the lower Yuba River downstream of Daguerre Point Dam, which indicates the importance of the superordinate planform. However, any existing theory on channel stability (e.g., Rosgen 1994; Huang and Nanson 2007) is adequate for explaining these changes quantitatively. The classification scheme from Huang and Nanson (2007), and also other approaches for the assessment of bifurcation stability (e.g., van Denderen et al., 2017), are based on 1D cross-section averaged flow characterisations. However, flow separation at bifurcations is a three-dimensional problem that needs to consider, among others, transverse bed slope (Bolla Pittaluga et al., 2003) and bend flow (Kleinhans et al., 2008). The literature (e.g., van Denderen et al., 2017) provides reasonable criteria for the construction of artificial side channels (see supplemental material) but the formation processes are not sufficiently understood and it is not possible to produce lifespan maps for this feature.

Structure removal (i.e., the removal of barriers for aquatic species and sediment transport continuity) cannot be quantified with lifespan maps. O'Hanley (2011) introduces an approach for the prioritisation of barriers to be removed based on fish benefits. However, this model lacks coupled hydro-morphological functions for predicting channel adjustments. Small transversal barriers with multi-purpose utility, such as irrigation, flood protection (sediment retention) or hydropower generation, can be alternatively improved with sophisticated fish passage and guiding strategies (e.g., King et al., 2016; Radinger et al., 2018).

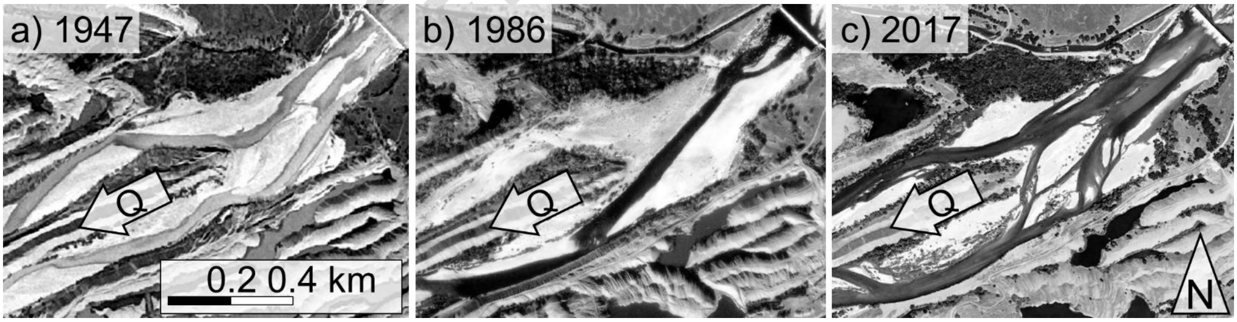

Figure 7: Closure and reactivation of a site channel of Lower Yuba River between 1947 (USGS, 1947), 1986 (USGS, 1986) and 2017 (Google Earth Pro, 2017).

4.2. Quantitative accuracy and validation

Uncertainties in accuracy occur at several stages in the process of creating lifespan maps. For example, imprecision originates from the exactness of the measuring instruments that were used for the exploration of survival thresholds (e.g., flow velocity), the precision of DEMs, hypotheses made in numerical modelling (e.g., usage of depth-averaged flow parameters) or discharge measurements and statistical methods for estimating flood return periods. The uncertainty is tangible in absolute numbers by using error propagation methods (e.g., DIN 1319-3, 1996) that require the knowledge of single errors and error functions. The number and complexity of error sources, as well as the difficulties in estimating errors in a large, multidisciplinary dataset make absolute quantification of lifespan map error challenging to assess. One of the major mitigating factors in potential error is the fact that the maps are not computing exact times with high precision. The use of broad bins spanning several years means that it is only required to be in the right bin, not yield an exact lifetime. Brown and Pasternack (2009) showed a similar beneficial effect on error impact when binning microhabitat and shear stress results from 2D models, which helps to reduce error. If the bins are reduced further to just a simple concept of low or high sustainability, then lifespan maps are even more resilient; the key is to not require any more precision than just necessary to answer the question at hand. When absolute numbers are relevant (e.g., for the diameter of riprap), safe assumptions are overestimated, such as values of D_{mobile} (i.e., an overestimation of the flow depth and velocity). By contrast, when restoration success is defined through grain mobilisation, as for example, in the case of gravel stockpiles, it is advantageous to underestimate grain sizes, flow depth and flow velocity.

The numeric validation of the computed lifespans as a function of the multiple parameters analysis requires the real implementation and observation of proposed features. Then, repetitive high-resolution satellite images can regularly provide information on the feature survival. Vegetation plantings may be followed-up with landscape complexity analysis (e.g., Papadimitrou, 2012). The stability of terraforming features and sediment replenishment can be analysed with landscape evolution models and the internal complexity of self-organizing erosion / deposition pattern (e.g., Schoorl et al., 2014).

4.3. Flood protection

The advantages of stream restoration for flood protection is well documented, particularly the attenuation of flood peaks through berm setback (e.g., Konrad et al., 2008; Opperman et al., 2010; Wohl et al., 2015). However, the additional roughness that constitute plantings or riprap slows down the flow and enhances sediment deposition (Järvelä, 2002). This happened, for example, after the restoration of the Swiss tributary "Arbogne", where fine sediment deposits in a restored river section caused regular flooding of neighbouring agricultural zones (De Cesare et al., 2016). 2D hydrodynamic models can indicate where sediment deposition occurs, when the roughness attributes are adapted to vegetation to account for the additional flow resistance that can cause fine sediment deposition (cf. descriptions in Järvelä, 2002).

Unsecured large woody material risks clogging at bridges during floods, which may cause inundation of infrastructure or even the entrainment of bridges (Piton and Recking, 2016). Where such concerns are present, stream restoration should consider sufficient anchoring of artificially placed wood (i.e., the installation of engineered logjams is preferable over placing loose logs).

4.4. Trade-off of lifespan maps

The current practice often uses ecological criteria for stream restoration planning (Buijs, 2009). Figure 5 shows that important shares of ecologically relevant restoration area have a low expected lifespans. This comparison suggests that the combination of morphological sustainability based on lifespan maps and the ecological relevance based on habitat suitability criteria help to identify ecologically and physically stable features. Thus, lifespan maps are a new and pertinent tool to foster the planning of eco-financially reasonable stream restoration.

5. Conclusions

Lifespan maps are an important tool for vetting ecological relevance against physical stability in stream restoration and habitat enhancement projects.

In agreement with the existing semantic framework of stream restoration goals, we parametrized and analysed the expected lifespans of restoration features at the Yuba River, California. The quantifiable parameters constitute, “survival thresholds” that determine the feature’s lifespans based on their physical stability. A comprehensive supplemental document summarises details.

The comparison of 2D hydrodynamic model results, morphological assessments and terrain DEMs with survival thresholds produces the lifespan maps. Thus, the lifespan maps indicate the potential site-specific longevity of particular restoration and habitat enhancement features.

Validated hydraulic and topographic input data ensure reasonable lifespan estimates. The validation of the accuracy of the estimated lifespans as a function of complex parameter interactions requires a follow-up of constructed features in the future.

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Appendix

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2018.11.010

References

Abu-Aly, T.R., Pasternack, G.B., Wyrick, J.R., Barker, R., Massa, D., Johnson, T., 2014. Effects of lidar-derived, spatially distributed vegetation roughness on two-dimensional hydraulics in a gravel-cobble river at flows of 0.2 to 20 times bankfull. Geomorphology 206, 468–482. doi:10.1016/j.geomorph.2013.10.017

Addy, S., Wilkinson, M., 2016. An assessment of engineered logjam structures in response to a flood event in an upland gravel-bed river. Earth Surface Processes and Landforms 41, 1658–1670. doi:10.1002/esp.3936

Ahmadi-Nedushan, B., St-Hilaire, A., Bérubé, M., Robichaud, É., Thiémonge, N., Bobée, B., 2006. A review of statistical methods for the evaluation of aquatic habitat suitability for instream flow assessment. River Research and Applications 22, 503–523. doi:10.1002/rra.918

Barker, J., Pasternack, G., Bratovich, P., Massa, D., Wyrick, J., Johnson, T., 2018. Kayak drifter surface velocity observation for 2D hydraulic model validation. River Research and Applications [in press], 1–11. doi:10.1002/rra.3238

Battisacco, E., Franca, M.J., Schleiss, A.J., 2016. Sediment replenishment: Influence of the geometrical configuration on the morphological evolution of channel-bed. Water Resources Research 52, 8879–8894. doi:10.1002/2016WR019157

Beatty, S., Allen, M., Lymbery, A., Jordaan, M.S., Morgan, D., Impson, D., Marr, S., Ebner, B., Weyl, O.L.F., 2017. Rethinking refuges: Implications of climate change for dam busting. Biological Conservation 209, 188–195. doi:10.1016/j.biocon.2017.02.007

Bennett, S.J., Ghaneeizad, S.M., Gallisdorfer, M.S., Cai, D., Atkinson, J.F., Simon, A., Langendoen, E.J., 2015. Flow, turbulence, and drag associated with engineered logjams in a fixed-bed experimental channel. Geomorphology 248, 172–184. doi:10.1016/j.geomorph.2015.07.046

Bernhardt, E.S., Palmer, M., Allan, J., Alexander, G., Barnas, K., Brooks, S., Carr, J., Clayton, S., Dahm, C., Follstad-Shah, J., others, 2005. Synthesizing U.S. river restoration efforts. Science 308, 636–637. doi:10.1126/science.1109769

Bernhardt, E.S., Sudduth, E.B., Palmer, M.A., Allan, J.D., Meyer, J.L., Alexander, G., Follastad-Shah, J., Hassett, B., Jenkinson, R., Lave, R., Rumps, J., Pagano, L., 2007. Restoring rivers one reach at a time: results from a survey of U.S. river restoration practitioners. Restorat. Ecol. 15 (3), 482–493. https://doi.org/10.1111/j.1526-100X.2007.00244.x.

Beschta, R.L., 1979. Debris removal and its effects on sedimentation in an Oregon Coast Range stream. Northwest Science 53, 71–77.

Beschta, R.L., Jackson, W.L., 1979. The Intrusion of Fine Sediments into a Stable Gravel Bed. Journal of the Fisheries Research Board of Canada 36, 204–210. doi:10.1139/f79-030

Blackbourn, D., 2006. The Conquest of Nature: Water, Landscape and the Making of Modern Germany. Pimlico, London, United Kingdom.

Bliem, M., Getzner, M., Rodiga-Laßnig, P., 2012. Temporal stability of individual preferences for river restoration in Austria using a choice experiment. Journal of Environmental Management 103, 65–73. doi:10.1016/j.jenvman.2012.02.029

Bolla Pittaluga, M., Coco, G., Kleinhans, M.G., 2015. A unified framework for stability of channel bifurcations in gravel and sand fluvial systems. Geophysical Research Letters 42, 7521–7536. doi:10.1002/2015GL065175

Bolla Pittaluga, M., Repetto, R., Tubino, M., 2003. Channel bifurcation in braided rivers: Equilibrium configurations and stability. Water Resources Research 39, 1–13. doi:10.1029/2001WR001112

Bolton, S., Shellberg, J., 2001. White Paper - Ecological Issues in Floodplains and Riparian Corridors. University of Washington, Seattle, WA, USA.

Bovee, K.D., 1986. Development and evaluation of Habitat Suitability Criteria for use in the instream flow incremental methodology (No. 21). National Ecology Center, U.S. Fish and Wildlife Service, Fort Collins, CO, USA.

Braudrick, C.A., Grant, G.E., 2000. When do logs move in rivers? Water Resources Research 36, 571–583. doi:10.1029/1999WR900290

Brooks, A.P., Gehrke, P.C., Jansen, J.D., Abbe, T.B., 2004. Experimental Reintroduction of woody debris on the Williams River, NSW: Geomorphic and ecological responses. River Research and Applications 20, 513–536. doi:10.1002/rra.764

Brown, R. A., Pasternack, G. B., 2009. Comparison of Methods for Analysing Salmon Habitat Rehabilitation Designs For Regulated Rivers. River Research and Applications 25, 745-772. doi:10.1002/rra.1189

Buijs, A.E., 2009. Public support for river restoration. A mixed-method study into local residents' support for and framing of river management and ecological restoration in the Dutch floodplains. Journal of Environmental Management 90, 2680–2689. doi:10.1016/j.jenvman.2009.02.006

Bunte, K., 2004. State of the science review. Gravel migration and augmentation below hydroelectric dams: A geomorphic perspective Report of Colorado State University, Engineering Research Center to U.S. Forest Service, Stream Systems Technology Center, Fort Collins, CO, USA.

Burns, J.W., 1970. Spawning bed sedimentation studies in northern California streams. California Fish and Game 56, 253–270.

Bywater-Reyes, S., Wilcox, A.C., Stella, J.C., Lightbody, A.F., 2015. Flow and scour constraints on uprooting of pioneer woody seedlings. Water Resources Research 51, 9190–9206. doi:10.1002/2014WR016641

Calflora, 2017. Information on california plants for education, research and conservation, with data contributed by public and private institutions and individuals, including the consortium of california herbaria. [web application]. search for plants.

Canadian Environmental Protection Act, 1999. CEPA.

Castro, J., Zamora, R., Hódar, J.A., 2006. Restoring Quercus pyrenaica forests using pioneer shrubs as nurse plants. Applied Vegetation Science 9, 137–142. doi:10.1111/j.1654-109X.2006.tb00663.x

Chang, H.H., 1985. Formation of Alternate Bars. Journal of Hydraulic Engineering 111, 1412–1420. doi:10.1061/(ASCE)0733-9429(1985)111:11(1412)

Church, M., 1983. Modern and Ancient Fluvial Systems (Collinson, J. D. and Lewin, J. (eds.)), in:. Blackwell Publishing Ltd., Oxford, UK, pp. 169–180. doi:10.1002/9781444303773.ch13

Cittero, A., Piégay, H., 2009. Overbank sedimentation rates in former channel lakes: characterization and control factors. Sedimentology 56, 461–482. doi:10.1111/j.1365-3091.2008.00979.x

Comiti, F., 2012. How natural are Alpine mountain rivers? Evidence from the Italian Alps. Earth Surface Processes and Landforms 37, 693–707. doi:10.1002/esp.2267

Crowder, D.W., Knapp, V.H., 2005. Effective discharge recurrence intervals of Illinois streams. Geomorphology 64, 167–184. doi:10.1016/j.geomorph.2004.06.006

De Cesare, G., Schwindt, S., Giroud, S., Maibach, A., Litsios-Dubuis, A., 2016. Evolution of a restored river course and alternative measures to correct unintended effects, in: Inter national Congress EFIB/AEIP Soil and Water Bioengineering. EFIB/AEIP, Donostia-San Sebastián, Spain, pp. 1–14.

DIN 1319-3, 1996. Grundlagen der Messtechnik [Basics of measurement technology]. Deutsches Institut für Normung e. V.

Du Boys, P., 1879. Etudes du régime du Rhône et l ’action exercée par les eaux sur un lit à fond de graviers indéfiniment affouillable [Studies of the flow of the Rhone and the forces exerted by the waters on an indefinitely erodible gravel bed]. Annales des Ponts et Chaussées 5, 141–195.

Dutta, S., Wang, D., Tassi, P., Garcia, M.H., 2017. Three-dimensional numerical modeling of the Bulle effect: the nonlinear distribution of near-bed sediment at fluvial diversions. Earth Surface Processes and Landforms 42, 2322–2337. doi:10.1002/esp.4186

Eaton, B.C., Church, M., Millar, R.G., 2004. Rational regime model of alluvial channel morphology and response. Earth Surface Processes and Landforms 29, 511–529. doi:10.1002/esp.1062

Edwards, P.J., Kollmann, J., Gurnell, A.M., Petts, G.E., Tockner, K., Ward, J.V., 1999. A conceptual model of vegetation dynamics on gravel bars of a large Alpine river. Wetlands Ecology and Management 7, 141–153. doi:10.1023/A:1008411311774

Einstein, H.A., 1950. The Bed-Load Function for Sediment Transport in Open Channel Flows. Technical Bulletin of the USDA Soil Conservation Service 1026, 71.

ESRI, 2017. ArcGIS Desktop: Release 10.5.

European Water Framework Directive, 2000. WFD.

Feio, M.J., Calapez, A.R., Elias, C.L., Cortes, R.M.V., Graça, M.A.S., Pinto, P., Almeida, S.F.P., 2016. The paradox of expert judgment in rivers ecological monitoring. Journal of Environmental Management 184, 609–616. doi:10.1016/j.jenvman.2016.10.004

Foley, M.M., Bellmore, J.R., O'Connor, J.E., Duda, J.J., East, A.E., Grant, G.E., Anderson, C.W., Bountry, J.A., Collins, M.J., Connolly, P.J., Craig, L.S., Evans, J.E., Greene, S.L., Magilligan, F.J., Magirl, C.S., Major, J.J., Pess, G.R., Randle, T.J., Shafroth, P.B., Torgersen, C.E., Tullos, D., Wilcox, A.C., 2017. Dam removal: Listening in. Water Resources Research 53, 5229–5246. doi:10.1002/2017WR020457

Formann, E., Egger, G., Hauer, C., Habersack, H., 2014. Dynamic disturbance regime approach in river restoration: concept development and application. Landscape and Ecological Engineering 10, 323–337. doi:10.1007/s11355-013-0228-5

Friedman, J.M., Auble, G.T., 1999. Mortality of riparian box elder from sediment mobilization and extended inundation. Regulated Rivers: Research & Management 15, 463–476. doi:10.1002/(SICI)1099-1646(199909/10)15:5<463::AID-RRR559>3.0.CO;2-Z

Gallisdorfer, M.S., Bennett, S.J., Ghaneeizad, S.M., Atkinson, J.F., 2016. Morphodynamic responses of physical-scale experimental river channels to engineered logjams for stream restoration design, in: Constantinescu, G., Garcia, M., Hanes, D. (Eds.), River Flow 2016. St. Louis, MO, USA, pp. 2354–2359.

Gattie, D.K., McCutcheon, S.C., Smith, M.C., 2003. Ecological engineering: the state-of-the-field. Ecological Engineering 20, 327–330. doi:10.1016/j.ecoleng.2003.09.004

Gilbert, G.K. 1917. Hydraulic-mining debris in the Sierra Nevada, Professional Paper 105. Department of the Interior, United States Geological Survey, 154p.

Gillenwater, D., Granata, T., Zika, U., 2006. GIS-based modeling of spawning habitat suitability for walleye in the Sandusky River, Ohio, and implications for dam removal and river restoration. Ecological Engineering 28, 311–323. doi:10.1016/j.ecoleng.2006.08.003

Google Earth Pro, 2017. Landsat / Copernicus (May 18, 2017). https://www.google.com/earth/desktop/.

Grant, G., 2001. Dam removal: Panacea or Pandora for rivers? Hydrological Processes 15, 1531–1532. doi:10.1002/hyp.473

Hassan, M., Brayshaw, D., Alila, Y., Andrews, E., 2014. Effective discharge in small formerly glaciated mountain streams of British Columbia: Limitations and implications. Water Resources Research 50, 4440–4458. doi:10.1002/2013WR014529

Hassan, M.A., Church, M., Lisle, T.E., Brardinoni, F., Benda, L., Grant, G.E., 2005. Sediment transport and channel morphology of small, forested streams. Journal of the American Water Resources Association 41, 853–876. doi:10.1111/j.1752-1688.2005.tb03774.x

Huang, H.Q., Nanson, G.C., 2007. Why some alluvial rivers develop an anabranching pattern. Water Resources Research 43, 1–12. doi:10.1029/2006WR005223

Jablkowski, P., Johnson, E.A., Martin, Y.E., 2017. Role of river flow and sediment mobilization in riparian alder establishment along a bedrock-gravel river, south fork eel river, california. Geomorphology 295, 28–38. doi:10.1016/j.geomorph.2017.06.010

Jackson, J.R., Pasternack, G.B., Wyrick, R., Joshua, 2013. Lower Yuab River Accord Monitoring and Evaluation program: Substrate of the Lower Yuba River (research report). University of California Davis, Davis, CA, USA.

Jaeggi, M.N.R., 1984. Formation and Effects of Alternate Bars. Journal of Hydraulic Engineering 110, 142–156. doi:10.1061/(ASCE)0733-9429(1984)110:2(142)

Janisch, T., Weichert, R., Bezzola, G.R., 2007. Verhalten von aufgelösten unstrukturierten Blockrampen [Behavior of unstructured block ramps]. Wasser Energie Luft 99, 146–152.

Järvelä, J., 2002. Flow resistance of flexible and stiff vegetation: a flume study with natural plants. Journal of Hydrology 269, 44–54. doi:10.1016/S0022-1694(02)00193-2

Juez, C., Bühlmann, I., Maechler, G., Schleiss, A.J., Franca, M.J., 2017. Transport of suspended sediments under the influence of bank macro-roughness. Earth Surface Processes and Landforms [in press], 1–14. doi:10.1002/esp.4243

Julien, P.Y., 2002. River mechanics. Cambridge University Press, UK.

Keulegan, G.H., 1938. Laws of turbulent flow in open channels. U.S. National Bureau of Standards.

King, S., Fraser, I., O’Hanley, J.R., 2016. Benefits transfer and the aquatic environment: An investigation into the context of fish passage improvement. Journal of Environmental Management 183, 1079–1087. doi:10.1016/j.jenvman.2016.09.041

Kleinhans, M.G., Jagers, H.R.A., Mosselman, E., Sloff, C.J., 2008. Bifurcation dynamics and avulsion duration in meandering rivers by one-dimensional and three-dimensional models. Water Resources Research 44, 1–31. doi:10.1029/2007WR005912

Kollongei, K.J., Lorentz, S.A., 2014. Connectivity influences on nutrient and sediment migration in the Wartburg catchment, KwaZulu-Natal Province, South Africa. Physics and Chemistry of the Earth, Parts A/B/C 67-69, 12–22. doi:10.1016/j.pce.2014.01.002

Kondolf, G.M., 1997. Hungry Water: Effects of Dams and Gravel Mining on River Channels. Environmental Management 21, 533–551.

Konrad, C.P., Black, R.W., Voss, F., Neale, C.M.U., 2008. Integrating remotely acquired and field data to assess effects of setback levees on riparian and aquatic habitats in glacial-melt water rivers. River Research and Applications 24, 355–372. doi:10.1002/rra.1070

Kramer, H., 1932. Modellgeschiebe und Schleppkraft [Modelling bed load and drag force]. Preußische Versuchsanstalt für Wasserbau und Schiffbau.

Kui, L., Stella, J.C., 2016. Fluvial sediment burial increases mortality of young riparian trees but induces compensatory growth response in survivors. Forest Ecology and Management 366, 32–40. doi:10.1016/j.foreco.2016.02.001

Lamb, M.P., Dietrich, W.E., Venditti, J.G., 2008. Is the critical Shields stress for incipient sediment motion dependent on channel-bed slope? Journal of Geophysical Research 113, F02008. doi:10.1029/2007JF000831

Lane, E.W., 1955. The importance of fluvial geomorphology in hydraulic engineering. Proceedings of the American Society of Civil Engineering 81, 1–17.

Lange, D., Bezzola, G.R., 2006. Schwemmholz Probleme und Lösungansätze [Driftwood problems and approaches for solutions]. Minor, H.-E, ed.: Mitteilung Nr. 188 der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie an der Eidgenössischen Technischen Hochschule Zürich, Zürich, Switzerland.

Leopold, L.B., Wolman, M.G., 1957. River Channel patterns: Braided meandering and straight. USGS professional paper 282-B, 45–62.

Li, R.M., Simons, D.B., Blinco, P.H., Samad, M.A., 1976. Probabilistic approach to design of riprap riverbank protection, in: Rivers 76: Proceedings of the Symposium on Inland Waterways for Navigation, Flood Control, and Water Diversions. Colorado State University; American Society of Civil Engineers, Fort Collins, CO, USA, pp. 1572–1591.

Lisle, T., 1979. A sorting mechanism for a riffle-pool sequence. Geological Society of America Bulletin 90, 1142–1157. doi:10.1130/GSAB-P2-90-1142

Lisle, T.E., Iseya, F., Ikeda, H., 1993. Response of a Channel with alternate bars to a decrease in supply of mixed-size bed load: A Flume Experiment. Water Resources Research 29, 3623–3629. doi:10.1029/93WR01673

Liu, X., Infante Sedano, J.Á., Mohammadian, A., 2015. A coupled two-dimensional numerical model for rapidly varying flow, sediment transport and bed morphology. Journal of Hydraulic Research 53, 609–621. doi:10.1080/00221686.2015.1085919

Makaske, B., Smith, D.G., Berendsen, H.J.A., de Boer, A.G., van Nielen-Kiezebrink, M.F., Locking, T., 2009. Hydraulic and sedimentary processes causing anastomosing morphology of the upper Columbia River, British Columbia, Canada. Geomorphology 111, 194–205. doi:10.1016/j.geomorph.2009.04.019

Manners, R.B., Doyle, M.W., Small, M.J., 2007. Structure and hydraulics of natural woody debris jams. Water Resources Research 43, 1–17. doi:10.1029/2006WR004910

Manners, R.B., Wilcox, A.C., Kui, L., Lightbody, A.F., Stella, J.C., Sklar, L.S., 2015. When do plants modify fluvial processes? Plant-hydraulic interactions under variable flow and sediment supply rates. Journal of Geophysical Research: Earth Surface 120, 325–345. doi:10.1002/2014JF003265

Maynord, S., Neill, C., 2008. Sedimentation Engineering, in: ASCE Manual and Reports on Engineering Practice No. 110. American Society of Civil Engineering, García, M. H. (ed.), Reston, VA, USA, pp. 1037–1056. doi:10.1061/9780784408148

McCoy, A., Constantinescu, G., Weber, L.J., 2008. Numerical Investigation of Flow Hydrodynamics in a Channel with a Series of Groynes. Journal of Hydraulic Engineering 134, 157–172. doi:10.1061/(ASCE)0733-9429(2008)134:2(157)

McManamay, R. A., Orth, D. J., Dolloff, C. A., Cantrell, M. A., 2011 Gravel Addition as a Habitat Restoration Technique for Tailwaters. North American Journal of Fisheries Management, 30, 1238–1257. doi: 10.1577/M10-007.1

Meile, T., Boillat, J.-L., Schleiss, A.J., 2011. Water-surface oscillations in channels with axi-symmetric cavities. Journal of Hydraulic Research 49, 73–81. doi:10.1080/00221686.2010.534671

Montgomery, D.R., Buffington, J., 1997. Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin 109, 596–611. doi:10.1130/0016-7606(1997)109<0596:CRMIMD>2.3.CO;2

Morandi, B., Piégay, H., Lamouroux, N., Vaudor, L., 2014. "How is success or failure in river restoration projects evaluated? Feedback from french restoration projects". Journal of Environmental Management 137, 178–188. doi:10.1016/j.jenvman.2014.02.010

Moyle, P.B., Mount, J.F., 2007. Homogenous rivers, homogenous faunas. Proceedings of the National Academy of Sciences of the United States of America 104, 5711–5712. doi:10.1073/pnas.0701457104

Nagayama, S., Nakamura, F., Kawaguchi, Y., Nakano, D., 2012. Effects of configuration of instream wood on autumn and winter habitat use by fish in a large remeandering reach. Hydrobiologia 680, 159–170. doi:10.1007/s10750-011-0913-z

Naiman, R.J., Décamps, H., 1997. The Ecology of Interfaces: Riparian Zones. Annual Review of Ecology and Systematics 28, 621–658. doi:10.1146/annurev.ecolsys.28.1.621

Nanson, G.C., Knighton, A.D., 1996. Anabranching Rivers: Their cause, character and classification. Earth Surface Processes and Landforms 21, 217–239. doi:10.1002/(SICI)1096-9837(199603)21:3<217::AID-ESP611>3.0.CO;2-U

Nezu, I., Onitsuka, K., 2002. PIV Measurements of side-cavity open-channel flows - Wando model in rivers. Journal of Visualization 5, 77–84. doi:10.1007/BF03182606

Norman, L.M., Sankey, J.B., Dean, D., Caster, J., DeLong, S., DeLong, W., Pelletier, J.D., 2017. Quantifying geomorphic change at ephemeral stream restoration sites using a coupled-model approach. Geomorphology 283, 1–16. doi:10.1016/j.geomorph.2017.01.017

NRCS, N., 2001. Incorporation of large wood into engineering structures, Technical Notes - Engineering No. 15. U.S. Department of Agriculture, Boise, ID, USA.

Ock, G., Sumi, T., Takemon, Y., 2013. Sediment replenishment to downstream reaches below dams: implementation perspectives. Hydrological Research Letters 7, 54–59. doi:10.3178/hrl.7.54

Opperman, J.J., Luster, R., McKenney, B.A., Roberts, M., Meadows, A.W., 2010. Ecologically Functional Floodplains: Connectivity, Flow Regime, and Scale. JAWRA Journal of the American Water Resources Association 46, 211–226. doi:10.1111/j.1752-1688.2010.00426.x

O'Connor, J.E., Duda, J.J., Grant, G.E., 2015. 1000 dams down and counting. Science 348, 496–497. doi:10.1126/science.aaa9204

O'Hanley, J.R., 2011. Open rivers: Barrier removal planning and the restoration of free-flowing rivers. Journal of Environmental Management 92, 3112–3120. doi:10.1016/j.jenvman.2011.07.027

Papadimitriou, F., 2012. The Algorithmic Complexity of Landscapes. Landscape Research 37, 591-611. doi: 10.1080/01426397.2011.650628

Pasquale, N., Perona, P., Francis, R., Burlando, P., 2014. Above-ground and below-ground Salix dynamics in response to river processes. Hydrological Processes 28, 5189–5203. doi:10.1002/hyp.9993

Pasquale, N., Perona, P., Francis, R., Burlando, P., 2012. Effects of streamflow variability on the vertical root density distribution of willow cutting experiments. Ecological Engineering 40, 167–172. doi:10.1016/j.ecoleng.2011.12.002

Pasquale, N., Perona, P., Schneider, P., Shrestha, J., Wombacher, A., Burlando, P., 2011. Modern comprehensive approach to monitor the morphodynamic evolution of a restored river corridor. Hydrology and Earth System Sciences 15, 1197–1212. doi:10.5194/hess-15-1197-2011

Pasternack, G.B., Gilbert, A.T., Wheaton, J.M., Buckland, E.M., 2006. Error propagation for velocity and shear stress prediction using 2D models for environmental management. Journal of Hydrology 328, 227–241. doi:10.1016/j.jhydrol.2005.12.003

Pasternack, G.B., Morford, S.L., Fulton, A.A., 2010. Yuba River analysis aims to aid spring-run chinook salmon habitat rehabilitation. California Agriculture 64, 69–77. doi:10.3733/ca.v064n02p69

Pasternack, G.B., Wyrick, J.R., 2017. Flood-driven topographic changes in a gravel-cobble river over segment, reach, and morphological unit scales. Earth Surface Processes and Landforms 42, 487–502. doi:10.1002/esp.4064

Piton, G., Carladous, S., Recking, A., Tacnet, J.M., Liébault, F., Kuss, D., Quefféléan, Y., Marco, O., 2017. Why do we build check dams in Alpine streams? An historical perspective from the French experience. Earth Surface Processes and Landforms 42, 91–108. doi:10.1002/esp.3967

Piton, G., Recking, A., 2017. The concept of travelling bedload and its consequences for bedload computation in mountain streams. Earth Surface Processes and Landforms (*in press*), 52. doi:10.1002/esp.4105

Piton, G., Recking, A., 2016. Design of Sediment Traps with Open Check Dams. II: Woody Debris. Journal of Hydraulic Engineering 142, 04015046. doi:10.1061/(ASCE)HY.1943-7900.0001049

Politti, E., Bertoldi, W., Gurnell, A., Henshaw, A., 2018. Feedbacks between the riparian Salicaceae and hydrogeomorphic processes: A quantitative review. Earth-Science Reviews 176, 147–165. doi:10.1016/j.earscirev.2017.07.018

Polzin, M.L., Rood, S.B., 2006. Effective disturbance: Seedling safe sites and patch recruitment of riparian cottonwoods after a major flood of a mountain river. Wetlands 26 (4), 965–980. https://link.springer.com/article/10.1672/0277-5212(2006)26%5B965:EDSSSA%5D2.0.CO;2.

QGIS, 2018. QGIS 2.8.

Radinger, J., Hölker, F., Horký, P., Slavík, O., Wolter, C., 2018. Improved river continuity facilitates fishes' abilities to track future environmental changes. Journal of Environmental Management 208, 167–176. doi:10.1016/j.jenvman.2017.12.011

Reichert, P., Borsuk, M., Hostmann, M., Schweizer, S., Spörri, C., Tockner, K., Truffer, B., 2007. Concepts of decision support for river rehabilitation. Environmental Modelling & Software 22, 188–201. doi:10.1016/j.envsoft.2005.07.017

Ricardo, A. M., 2014. Hydrodynamics of turbulent flows within arrays of circular cylinders (LCH Communication 57). Laboratory of Hydraulic Constructions (LCH), Ecole Polytechnique fédérale de Lausanne. EPFL. doi:10.5075/epfl-lchcomm-57

Rickenmann, D., 1990. Bedload transport capacity of slurry flows at steep slopes (PhD thesis No. 103). Mitteilungen der Versuchsanstalt fur Wasserbau, Hydrologie und Glaziologie an der Eidgenossischen Technischen Hochschule Zurich. ETHZ. doi:10.3929/ethz-a-000555802

Rickenmann, D., Recking, A., 2011. Evaluation of flow resistance in gravel-bed rivers through a large field data set. Water Resources Research 47, W07538. doi:10.1029/2010WR009793

Rinaldi, M., Belletti, B., Bussettini, M., Comiti, F., Golfieri, B., Lastoria, B., Marchese, E., Nardi, L., Surian, N., 2017. New tools for the hydromorphological assessment and monitoring of European streams. Journal of Environmental Management 202, 363–378. doi:10.1016/j.jenvman.2016.11.036

Riquier, J., Piégay, H., Lamouroux, N., Vaudor, L., 2017. Are restored side channels sustainable aquatic habitat features? Predicting the potential persistence of side channels as aquatic habitats based on their fine sedimentation dynamics. Geomorphology 295, 507–528. doi:10.1016/j.geomorph.2017.08.001

Rockwell, D., Naudascher, E., 1978. Review - Self-Sustaining Oscillations of Flow Past Cavities. Journal of Fluids Engineering 100, 152–165. doi:10.1115/1.3448624

Rosatti, G., Zugliani, D., 2015. Modelling the transition between fixed and mobile bed conditions in two-phase free-surface flows: The Composite Riemann Problem and its numerical solution. Journal of Computational Physics 285, 226–250. doi:10.1016/j.jcp.2015.01.011

Rosgen, D.L., 1994. A classification of natural rivers. Catena 22, 169–199.

Ruiz-Villanueva, V., Bladé, E., Sánchez-Juny, M., Marti-Cardona, B., Díez-Herrero, A., Bodoque, J.M., 2014a. Two-dimensional modelling of large wood transport. J. Hydroinf. 16, 1077–1096. https://doi.org/10.2166/hydro.2014.026.

Ruiz-Villanueva, V., Bodoque, J.M., Díez-Herrero, A., Bladé, E., 2014b. Large wood transport as significant influence on flood risk in a mountain village. Nat. Hazards 74, 967–987. https://doi.org/10.1007/s11069-014-1222-4.

Ruiz-Villanueva, V., Wyzga, B., Zawiejska, J., Hajdukiewicz, M., Stoffel, M., 2016. Factors controlling large-wood transport in a mountain river. Geomorphology 272, 21–31. https://doi.org/10.1016/j.geomorph.2015.04.004.

Schleiss, A.J., 2017. Better water infrastructures for a better world - The important role of water associations. hydrolink 3, 86–87.

Schleiss, A.J., Studer, M.J., 2016. Discussion of Experimental study on the flow characteristics of unstructured block ramps by Simona Tamagni, Volker Weitbrecht and Robert M. Boes. Journal of Hydraulic Research 54, 242–243. doi:10.1080/00221686.2015.1137641

Schoorl, J. M., Temme, A. J. A. M., Veldkamp, T., 2014. Modelling centennial sediment waves in an eroding landscape – catchment complexity. Earth Surface Processes and Landforms 39, 1526-1537. doi: 10.1002/esp.3605

Schumm, S.A., 1985. Patterns of alluvial rivers. Annual Review of Earth Planetary Sciences 13, 5–27.

Schwindt, S., Franca, M.J., Reffo, A., Schleiss, A.J., 2018. Sediment traps with guiding channel and hybrid check dams improve controlled sediment retention. Natural Hazards and Earth System Science [accepted for publication], 25.

Shields, A., 1936. Anwendung der Ähnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung [Application of the similarity in mechanics and turbulence research on the mobility of bed load]. Preußische Versuchsanstalt für Wasserbau und Schiffbau, Berlin, Germany.

Stamou, A., Polydera, A., Papadonikolaki, G., Martínez-Capel, F., Muñoz-Mas, R., Papadaki, C., Zogaris, S., Bui, M.-D., Rutschmann, P., Dimitriou, E., 2018. Determination of environmental flows in rivers using an integrated hydrological-hydrodynamic-habitat modelling approach. Journal of Environmental Management 209, 273–285. doi:10.1016/j.jenvman.2017.12.038

Sternecker, K., Wild, R., Geist, J., 2013. Effects of substratum restoration on salmonid habitat quality in a subalpine stream. Environmental Biology of Fish 96, 1341–1351. doi:10.1007/s10641-013-0111-0

Stevens, M.A., Simmons, D.B., Lewis, G.L., 1976. Safety factors for riprap protection. Journal of the Hydraulics Division 102, 637–655.

Stiles, R., 1988. Engineering with vegetation. Landscape Design 172, 57–61.

Stillwater Sciences, 2006. Merced River ranch channel-floodplain restoration design rationale technical memorandum #8, Merced River corridor restoration plan phase IV: dredger tailings reach. Recipient Agreement No. ERP-02-P12-D. Merced River Stakeholder Group and Technical Advisory Committee, Prepared for CALFED, Berkeley, CA, USA. http://merced.stillwatersci.com/pdf/8/TM8_Design%20Rationale_compiled.pdf.

Stromberg, J.C., Richter, B.D., Patten, D.T., Wolden, L.G., 1993. Response of a Sonoran Riparian forest to a 10-year return flood. The Great Basin Naturalist 53, 118–130.

Surian, N., Rinaldi, M., 2003. Morphological response to river engineering and management in alluvial channels in Italy. Geomorphology 50, 307–326. doi:10.1016/S0169-555X(02)00219-2

SYRCL, 2013. Hammon Bar Riparian Enhancement Project Report. South Yuba River Citizens League (Reedy, Gary and Dion, Gerald and Ride, Adele and Della Santina, Denise and Phillips, Sarah and Hutchinson, Rachel), Nevada City, CA, USA.

Tiffan, K.F., Garland, R.D., Rondorf, D.W., 2002. Quantifying Flow-Dependent Changes in Subyearling Fall Chinook Salmon Rearing Habitat Using Two-Dimensional Spatially Explicit Modeling. North American Journal of Fisheries Management 22, 713–726. doi:10.1577/1548-8675(2002)022<0713:QFDCIS>2.0.CO;2

Tulla, J.G., 1812. Die Grundsätze, nach welchen die Rheinbauarbeiten künftig zu führen seyn möchten [The principle according to which the future construction works at the Rhine need to be managed].

Tullos, D.D., Collins, M.J., Bellmore, J.R., Bountry, J.A., Connolly, P.J., Shafroth, P.B., Wilcox, A.C., 2016. Synthesis of Common Management Concerns Associated with

Dam Removal, JAWRA Journal of the American Water Resources Association 52, 1179–1206. doi:10.1111/1752-1688.12450

U.S. National Environmental Policy Act, 1969. NEPA.

Uno, K., Kazuuma, N., Tsujimoto, G., Kakinoki, T., 2013. Trapping effect of fine sediment in Wandos. Journal of Japan Society of Civil Engineers, Ser. B3 (Ocean Engineering) 69, 922–927. doi:10.2208/jscejoe.69.I_922

USACE, 1994. Hydraulic Design of Flood Control Channels, in: Engineering and Design, Engineer Manual. U.S. Army Corps of Engineers, Washington, DC, USA, p. 183.

USACE, YCWA, 2016. Yuba River Ecosystem Restoration Feasibility Study (YRERFS) - Habitat Measures. Yuba County Water Agency (YCWA), Sacramento, CA.

USGS, 1947. Airborne Imagery from the United States Geological Survey.

USGS, 1986. Airborne Imagery from the United States Geological Survey.

van Denderen, R.P., Schielen, R.M.J., Blom, A., Hulscher, S.J.M.H., Kleinhans, M.G., 2017. Morphodynamic assessment of side channel systems using a simple one-dimensional bifurcation model and a comparison with aerial images. Earth Surf. Process. Landforms 14. https://doi.org/10.1002/esp.4267. (in press).

Vehanen, T., Bjerke, P.L., Heggenes, J., Huusko, A., Mäki-Petäys, A., 2000. Effect of fluctuating flow and temperature on cover type selection and behaviour by juvenile brown trout in artificial flumes. Journal of Fish Biology 56, 923–937. doi:10.1111/j.1095-8649.2000.tb00882.x

Vesipa, R., Camporeale, C., Ridolfi, L., 2017. Effect of river flow fluctuations on riparian vegetation dynamics: Processes and models. Advances in Water Resources 110, 29–50. doi:10.1016/j.advwatres.2017.09.028

Von Karmàn, T., 1930. Mechanische Ähnlichkeit und Turbulenz [Mechanical similarity and turbulence], in: Third International Congress for Applied Mechanics. Stockholm, pp. 79–93.

Weber, M.D., Pasternack, G.B., 2017. Valley-scale morphology drives differences in fluvial sediment budgets and incision rates during contrasting flow regimes. Geomorphology 288, 39–51. doi:10.1016/j.geomorph.2017.03.018

Weber, C., Schager, E., Peter, A., 2009. Habitat diversity and fish assemblage structure in local river widenings: A case study on a Swiss river. River Research and Applications 25, 687–701. doi:10.1002/rra.1176

Weitbrecht, V., Tamagni, S., Boes, R., 2017. Stability of Unstructured Block Ramps. Journal of Hydraulic Engineering 143, 04016095–1–9. doi:10.1061/(ASCE)HY.1943-7900.0001259

Wheaton, J.M., Brasington, J., Darby, S.E., Sear, D.A., 2010. Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. Earth Surface Processes and Landforms 35, 136–156. doi:10.1002/esp.1886

Wilcox, A.C., Shafroth, P.B., 2013. Coupled hydrogeomorphic and woody-seedling responses to controlled flood releases in a dryland river. Water Resources Research 49, 2843–2860. doi:10.1002/wrcr.20256

Williams, G.P., 1978. Bank-Full Discharge of Rivers. Water Resources Research 14, 1141–1154. doi:10.1029/WR014i006p01141

Wohl, E., Lane, S.N., Wilcox, A.C., 2015. The science and practice of river restoration. Water Resources Research 51, 5974–5997. doi:10.1002/2014WR016874

Wohl, E.E., 2000. Mountain rivers. American Geophysical Union, Washington, DC.

Wolman, M.G., Miller, J.P., 1960. Magnitude and frequency of forces in geomorphic processes. The Journal of Geology 68, 54–74.

Woolsey, S., Capelli, F., Gonser, T., Hoehn, E., Hostmann, M., Junker, B., Paetzold, A., Roulier, C., Schweizer, S., Tiegs, S.D., Tockner, K., Weber, C., Peter, A., 2007. A strategy to assess river restoration success. Freshwater Biology 52, 752–769. doi:10.1111/j.1365-2427.2007.01740.x

YCWA, 2013. Instream flow above Englebright Reservoir, in: Yuba River Development Project, FERC Project No. 2246. Yuba County Water Agency, Marysville, CA, USA, p. 32.