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Spawning habitat rehabilitation – I. Conceptual approach and methods

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ABSTRACT
Altered sediment and flow regimes in regulated rivers limit available spawning habitat for many fishes, especially salmonids. Mitigation efforts include spawning habitat rehabilitation and dam-removal, but often neglect conceptual or predictive models of hydrogeomorphic and ecological processes. Complete restoration of processes necessary for maintaining spawning habitat is often unrealistic in regulated rivers. However, we present a framework for spawning habitat rehabilitation based on the premise that certain ecologic functions and geomorphic processes can be restored in a manner that facilitates testing of underlying scientific theories. SHIRA (Spawning Habitat Integrated Rehabilitation Approach) provides a science-based, systematic framework for reach-scale rehabilitation of salmonid spawning habitat in regulated rivers. This approach is driven by a mix of field data, conceptual models and numerical models to provide predictive and explanatory insight into the rehabilitation process. Conceptual models are advocated for developing multiple design scenarios and explicit hypotheses about hydrogeomorphic processes and ecologic functions provided by said designs. Hydrodynamic, habitat suitability and sediment entrainment models that test the potential validity of design hypotheses prior to construction are reviewed. It is presumed that the added insight would improve the outcome of rehabilitation projects and test underlying scientific theories against the rigors of real-world uncertainties.

Keywords: River restoration; gravel augmentation; spawning gravels; habitat enhancement; salmonid spawning beds; restoration design.

1 Introduction

Throughout the Northern Hemisphere, rivers that once sustained robust anadromous salmon and trout runs are now regulated, harnessed, or otherwise impacted by dams, diversions, chanelisation and instream gravel mining (Graf, 2001; Marmulla, 2001). The decline of salmonids in regulated rivers has been linked to many perturbations including over-harvest and inaccessibility, degradation and reduction of spawning habitat for these fish (Moyle and Randall, 1998; Nehlsen *et al.*, 1991; Yoshiyama *et al.*, 1998). For three decades, efforts in North America and Europe to restore the health of salmon fisheries have included spawning habitat rehabilitation (SHR) projects (Brookes, 1996) (Figure 1). Most SHR projects lack science-based designs (NRC, 1992), and instead attempt to mimic the form of analogue reaches based on local knowledge and an ad hoc implementation (Kondolf, 2000b). Hydrogeomorphic processes are frequently neglected and monitoring is often inadequate (Sear, 1994). Project failure is not uncommon (NRC, 1992) and success can be difficult to assess accurately due to inadequate monitoring and unclear objectives (Downs and Kondolf, 2002). SHR is based on the ecological concept of indicator species (Willson and Halupka, 1995). The concept suggests that there exist species whose needs are similar to and reflect the needs of a broader group of species, and whose abundance is an indicator of ecosystem health. Thus, SHR focuses on improving spawning habitat, because such improvements can also yield benefits to fish during multiple life stages, macroinvertebrates and the entire food web (Merz, in press). Despite uncertainty in using indicator species as the basis for river rehabilitation (Anderson *et al.*, 2003), single-species recovery of socially and economically important fish is a political and funding reality for agencies, practitioners and river managers (Brookes *et al.*, 1996). Furthermore, SHR is commonly required for dam re-licensing (e.g. FERC, 1998) and will likely continue for some time until broader ecosystem restoration approaches might prevail. Our premise for this paper is, in the interim much

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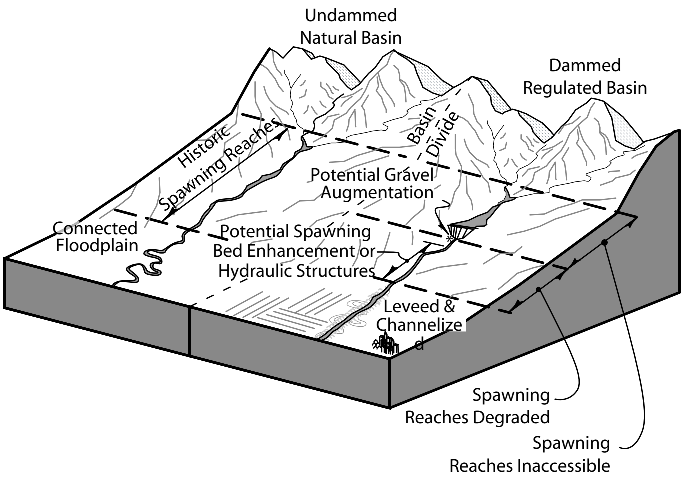

Figure 1 Context of spawning habitat rehabilitation. Regulated rivers alter basin-scale hydrogeomorphic processes, block access to historic spawning habitat upstream of dams and degrade historic spawning habitat downstream of dams. Hypothetical locations of three types of spawning habitat rehabilitation activities downstream of a dam are shown in the regulated basin.

can be learnt from SHR and incremental improvements in practice are realistic.

No clear consensus emerges from the literature on the definition of river restoration much less SHR (e.g. Boon, 1998; Sear, 1994; Shields *et al.*, 2003). Here, SHR is segregated into three categories: (1) gravel augmentation, (2) hydraulic structure placement and (3) spawning bed enhancement. Gravel augmentation (also known as gravel injection, infusion or replenishment) involves dumping clean spawning gravels into piles along the edges of a river (usually just downstream of a dam). For this approach to yield usable spawning habitat, practitioners must assume that high flows occur in the near future, that augmented gravels entrain during high flows, and that gravels do not fill mining holes or pools but instead deposit as bars or riffles. Hydraulic structure placement entails placement of large woody debris (LWD), boulder clusters, v-dams or similar structures to alter hydrodynamics in such a way that spawning gravels are deposited in the vicinity of the structures (Brookes *et al.*, 1996). The technique relies on an adequate supply of gravel from upstream and an active bedload transport regime to deliver it. Such structures may also be intended to provide refugia, cover and add habitat heterogeneity (Van-Zyll-De-Jong *et al.*, 1997). Spawning bed enhancement is the direct modification of the bed to provide immediate spawning habitat (e.g. riffle construction, bed ripping and riffle cleansing). Although bed enhancement may quickly provide usable spawning habitat, limited project lifespan may result without adequate consideration of geomorphic processes or regular gravel replenishment (Kondolf, 2000b). In summary, SHR projects are typically reach-scale restoration activities sometimes, but not necessarily, nested within a larger, long-term, basin-scale management plan (e.g. McBain and Trush, 1997).

SHR lacks a comprehensive design and implementation approach published in the peer-reviewed literature. Generalized outlines for stream restoration (FISRWG, 1998), and more specific guidelines incorporating fluvial geomorphology (Brookes and Sear, 1996; Gilvear, 1999; Sear, 1994), ecosystem theory (Stanford *et al.*, 1996) and design procedures (Hey *et al.*, 1994; Miller *et al.*, 2001; Shields *et al.*, 2003; Soar and Thorne, 2001) have been put forth in both the peer-reviewed and grey literature. It appears Kondolf (2000b) is one of the few authors to offer some fundamental considerations for SHR. The scattered examples of technical reports and grey literature, which mention SHR design rely on fairly basic, non-process based, best-management-practice recommendations (e.g. Slaney and Zaldokas, 1997). Only occasional pre and post-project assessments of SHR have been reported (e.g. Harper *et al.*, 1998; Kondolf *et al.*, 1996) and overviews of common practices are sparse (e.g. Brookes *et al.*, 1996). Where more sophisticated analyses of SHR based on hydrodynamic and habitat modelling have been performed, they provide little design insight (e.g. Hardy and Addley, 2001; Lacey and Millar, 2001). The problems with applying the plethora of existing published restoration approaches to SHR is they focus on what to do as opposed to how to do it; and they are not actively used by SHR practitioners (something this paper does not address). We presume the later is due to a combination of lack of specific implementation directions and the reality that most approaches are published in scientific journals, not easily accessible to practitioners, or in grey literature reports that are often difficult to find.

Several themes in the river restoration literature point towards some methodological consensus. Similar to Hildén (2000), we hypothesize that if restoration science and practice are to proceed collaboratively, a design approach drawing on scientific concepts and tools from multiple disciplines should be used (i.e. the familiar but vague buzzwords: adaptive, holistic and integrated still apply). In reality, this hypothesis is virtually impossible to test and the transferability of results from case studies to other projects can only hint at its validity or falseness. For practitioners, such a design approach should provide mechanistic understanding and predictive capability to the hydrogeomorphic and ecological underpinnings of SHR (Annable, 1999). For scientists, the designs should put our underlying theories about the interaction of hydrogeomorphic processes and ecologic functions to the test. Most agree that a "process-based" approach is superior to "form mimicry" (Kondolf, 1995b), but considerable discrepancies arise when one labels another's approach as "form mimicry" (Wilcock, 1997). Part of the confusion stems from both the difficulty and appropriateness in selecting an analogue condition (either from historical evidence or a present day location). In referring to an analogue condition, does one mimic the desired form or the desired process? Alternatively, analogue conditions can be abandoned and process focused on exclusively. The restoration literature generally supports the model of adaptive management (Clark, 2002). However, Walters (1997) astutely highlights four reasons why there has been such poor success in implementing adaptive management policies in restoration practice and river basin management: (1) over-reliance and faith in modelling to provide "best use" policies; (2) effective experiments are too expensive; (3) strong institutional opposition to experimental policies and breaking status-quo; and (4) deep environmental value conflicts within management. Finally, there is widespread recognition of the importance of adopting a watershed or catchment approach to restoration (Pess *et al.*, 2003), but confusion over whether this means: (a) restore the entire catchment (Frissell *et al.*, 1993); (b) use watershed assessments to nest reach scale restoration in a catchment context (Bohn and Kershner, 2002; Walker *et al.*, 2002); or (c) undertake a range of management and restoration activities across various spatial scales but nested within a catchment context (Roni *et al.*, 2002).

Two areas where fundamental methodological differences arise in restoration is with respect to passive versus active approaches (Edmonds *et al.*, 2003; Wissmar and Beschta, 1998). Referring to our three types of SHR as an example, gravel augmentation is a passive approach that relies on the river to do the work. By contrast, spawning bed enhancement and hydraulic structure placement are active approaches, which intervene because natural or passive recovery may take an unacceptably long time (Montgomery and Bolton, 2003). The choice of passive versus active will depend very much on the specific social, political, economic and environmental context of specific river basins (Wissmar *et al.*, 2003). In some cases, it may be appropriate to employ passive approaches like gravel augmentation in concert with active approaches like spawning bed enhancement.

In this paper, we review the application of a variety of existing science-based tools and concepts to design and analyze SHR projects in regulated rivers and suggest a framework within which those tools may be employed. To draw on the terminology above, the proposed framework is by choice interdisciplinary, process-based and adaptive; but by default it is active. That is, because the approach provides guidelines for spawning bed enhancement and hydraulic structure placement forms of SHR it is active. Our proposed framework is based primarily on our own attempts at SHR on the Mokelumne River, California and synthesis of the restoration literature. In a companion paper (Wheaton *et al.*, 2004), we present partial results of hypothesis testing during design using a case study on the Mokelumne River. More assessments across a broad range of biological, engineering, and geomorphic criteria are underway and will be reported subsequently.

2 Spawning Habitat Integrated Rehabilitation Approach

We did not formalize the concepts presented in this paper into the Spawning Habitat Integrated Rehabilitation Approach (SHIRA) to provide a step-by-step laundry list for practitioners. Much of SHIRA is intuitive and based on concepts and tools already well established in the literature and to a lesser extent in practice. Instead, we target a perceived gap between restoration science, which produces approaches detailing what restoration should be doing or assessments of what has been done wrong, and restoration practitioners charged with the daunting task of figuring out how to do it. Wilcock (1997) argues, it is not that the critiques and suggested approaches of science are faulty, but that they are ineffective. To this end, practitioners looking for guidance in how to design SHR projects might find SHIRA useful. Whereas, scientists or academics interested in testing the application of their theories in restoration might use SHIRA as a concise review of SHR. Although we know of no such approach for SHR in the peer-reviewed literature, we humbly acknowledge the parallels in structure SHIRA has with existing restoration approaches and guidelines (e.g. Brookes and Shields, 1996; FISRWG, 1998; NRC, 1992; Waal *et al.*, 1998). As with most approaches, SHIRA advocates comprehensive pre-project assessment, planning and design phases followed by construction, post-project assessment, monitoring and hopefully adaptive management. During each of seven *phases,* four primary *modes* are used iteratively to collect and analyze data on which flexible and informed decisions can be based (Figure 2). In Section 4.2, extra emphasis is provided on the design development stage, which is largely underdeveloped in SHR. Specific methods that are well established in the literature are only referenced for brevity.

Recall that SHR is typically reach-scale in implementation and SHIRA is focused on application in regulated rivers. Hence, how can practitioners carry out reach scale projects, while being mindful of basin scale processes? In any river system, the means to carry out "basin-scale management" are ambiguous and challenged with uncertainties due to variable socio-political drivers

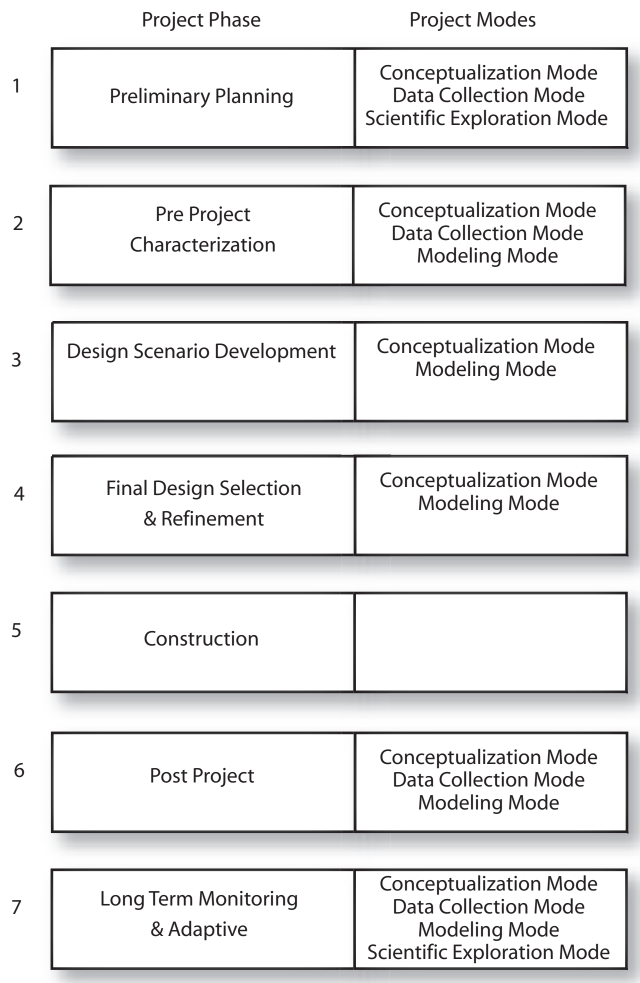

Figure 2 SHIRA Framework. Four modes (right hand side) are used to perform analyses and guide the decision making process in seven distinct phases (left hand side).

as well as lack of scientific knowledge (Anderson *et al.*, 2003). One conciliation of SHR in regulated rivers is that the basin context is dramatically simplified due to a phenomenon Stanford *et al.* (1996) term the serial discontinuity concept. That is, the ecological and geomorphic consequences of dams are largely predictable, and hence simplify consideration of basin scale drivers (Kondolf, 1997; Ligon *et al.*, 1995). Especially when SHR is carried out downstream of major dams (Figure 1), the uncertainty in flow regime is constrained by dam operations and the uncertainty in sediment supply from the upper basin is negligible because the dam is incapable of passing it. Thus, we assume and advocate that SHR under SHIRA is nested within a broader basin-scale management and assessment scheme (e.g. Montgomery *et al.*, 1995), but take advantage of the simplifications due to flow regulation.

3 SHIRA modes: Tools to encourage objective designs

3.1 Conceptualization mode

Design includes a creative process that enumerates multiple potential solutions. Preferably, those solutions are then analyzed to support a transparent decision to either proceed with a final design or not continue with the project (Clark and Richards, 2002). Because rivers are open systems, the design process will always have multiple "correct" solutions. Ideally, quantitative modelling and systems optimization might be used to create and select design alternatives, but there are many reasons why this cannot work. For example, the degrees of freedom that a computer would need to evaluate far exceed possibilities for the foreseeable future (Pasternack *et al.*, in press). Furthermore, mathematical models for many processes relevant to SHR do not exist and their uncertainties are poorly understood. A wealth of qualitative and empirical scientific conceptual models exist among ecology, hydrology, geomorphology and engineering (Table 1). On a site-by-site basis, conceptual models help designers plan and analyze projects. Rigid guidelines for applying conceptual models to design processes is inappropriate as the concepts for each project should be carefully chosen by a multidisciplinary team of local experts familiar with local conditions.

The design team may develop its own conceptual model(s) to explicitly and transparently document their understanding of how the specific river system functions. For example, a conceptual salmonid spawning habitat model was prepared to guide SHIRA on the Mokelumne River (Figure 3). This conceptual model asserts that where a female chooses to construct a redd is controlled by a mixture of ecological, geomorphic and hydrologic factors. At the basin scale, inherent factors (geology, topography, soils, climate, vegetation and human activities) yield river discharge and constituent loadings. Discharge and loadings are independent driving forces imposed on a reach to yield local flow and substrate conditions that interact to create physical habitat, which influences spawning site selection. Habitat heterogeneity, including hydraulic structures, proximity to refuge, patch size and patch mosaic variability, is an important feature of spawning conditions at the sub-reach scale. Redd construction itself alters

Table 1 Some potential conceptual models and their sources for use in the conceptualization mode.

Conceptual model	Source
Ecology	
Salmonid redd development	Chapman, 1988
Physical habitat assessments	Maddock, 1999
River continuum concept	Mishnall *et al.*, 1985
Primary controlling variables and biophysical interactions of river ecosystems	Stanford *et al.*, 1996
Conceptualization of riparian and hydrarch successional diversity in dynamic and regulated rivers	Ward *et al.*, 2001
Hydrogeomorphology	
Secondary flow cells	Booker *et al.*, 2001
Geomorphic thresholds	Church, 2002
Hydraulic geometry	Leopold and Maddock, 1953
Sediment transport (Chapter 4)	Knighton, 1998
The sediment supply system	Sear, 1996a; Sear, 1994
Sediment transport processes in pool-riffle sequences	Sear, 1996b
Revised velocity reversal hypothesis as pool maintenance mechanism	Thompson and Hoffman, 2001; Thompson *et al.*, 1999
Effective discharge	Wolman and Miller, 1960
Bankfull discharge	Wolman and Leopold, 1957
Integrated/Restoration	
Conceptualized continuum of regulated and unregulated rivers	Stanford *et al.*, 1996
River styles	Brierley and Fryirs, 2000; Thomson *et al.*, 2001
Living river strategy	Pedroli *et al.*, 2002
Disturbance regimes in riverine landscape	Poudevigne *et al.*, 2002
Spatial and temporal scales in river restoration	Sear, 1994
Five dimensions of river restoration	Boon, 1998
Potential influences of human activities on riverine attributes and processes	Wissmar and Beschta, 1998

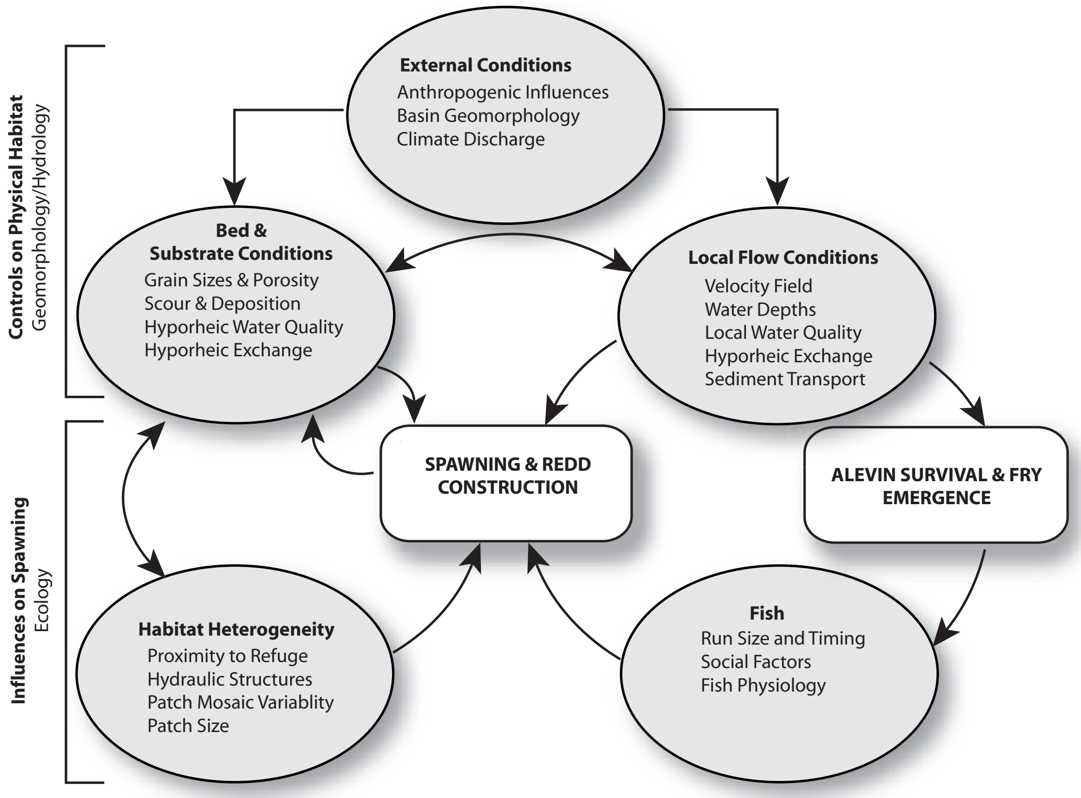

Figure 3 Conceptual spawning habitat model. The arrows indicate influences, the circles represent processes and characteristics, and the boxes are the outcomes. A combination of hydrogeomorphic processes spanning a range of scales combine to create physical habitat. Physical habitat is chosen by females for redd construction based on the ecologic functions provided by physical habitat and ecologic factors including habitat heterogeneity, run size, timing, social factors and physiology. The survival of alevins and ultimate emergence of fry is then primarily controlled by the substrate and local flow conditions during the incubation period.

local bed and flow conditions. In addition to physical factors, there are a host of ecological influences on spawning habitat utilization, including run size, run timing, competition, predation, hatchery management, harvest, social and physiological factors. The success of egg development and the ultimate emergence of fry are controlled by local flow and substrate conditions throughout the incubation period. For example, flood disturbance may produce local scour to egg burial depth or deposition of fines that infiltrates pores and prevent flushing of metabolic wastes (Lisle and Lewis, 1992).

A conceptual understanding of channel form and the primary process controls, which create, maintain, modify or destroy spawning habitat is essential. Four components comprise geomorphic analysis in the conceptualization mode: (1) geomorphic mapping, (2) empirical geomorphic analysis, (3) sediment budget and (4) geomorphic process inventory. First, a multi-scalar geomorphic classification scheme should be used to map morphology so that process inferences can be made across multiple scales (e.g. Maddock, 1999; Sear *et al.*, 1995; Thomson *et al.*, 2001). Second, an empirical geomorphic analysis of hydraulic geometry data derived from topography and flow records explains how flow and channel shape respond to changes in discharge (refer to: Leopold and Maddock, 1953). Third, sediment budgets quantify sediment supply, storage, and export (e.g. McLean and Church, 1999; Reid and Dunne, 1996). Because river regulation alters the sediment budget and flow regime, a sediment budget is needed at the basin-scale to characterize the distribution of aggradation versus degradation. Finally, a process inventory helps pinpoint problems and potential solutions. For example, if spawning substrate quality deteriorates due to an intrusion of fines, is it the result of fine-sediment production from land use changes or a flow regime incapable of flushing fines? The process inventory can be conceptual (i.e. field reconnaissance) or more quantitative, involving detailed process measurements (Thorne, 1998).

3.2 Modelling mode

SHIRA draws on quantitative modelling tools to make specific predictions about hydrogeomorphic and ecological processes. Empirical concepts used in river restoration employ a best-fit line to identify design specifications at cross-sections (e.g. Rosgen, 1996). However, acceptable errors in log-log trends for first-order science far exceed that for practical, sustainable design. Individual reaches have unique processes and morphologies that defy empirical prediction (Kondolf, 1995b). In contrast, high-resolution numerical models can simulate and predict unique river features, thereby making such models useful for design and analysis.

3.2.1 Digital elevation modelling

High quality digital elevation models (DEMs) and derived topographic maps are invaluable for planning, design and analysis, and critical to the success of predictive 2D hydrodynamic models (French and Clifford, 2000). A number of methods and software applications are available to create DEMs from topographic survey point data (e.g. ACAD™, ARC™, MATLAB™, Surfer™). The spatial distribution of these points (e.g. random, grid, irregular, stratified) help determine which interpolation method is most appropriate to create a DEM. For highly irregularly distributed data sets, simple linear interpolation algorithms that use triangular irregular networks (TINs) tend to produce the most realistic DEMs (McCullagh, 1981). Although many hydrodynamic model interfaces provide basic DEM development tools, computer assisted drafting provides more powerful DEM editing, refinement and management capabilities in design contexts. French and Clifford (2000) suggest that DEM development consists of four iterative stages that are repeated until DEM quality is satisfactory: (1) visualization, (2) editing, (3) augmentation and (4) interpolation.

3.2.2 Hydrodynamic modelling

Hydrodynamic modelling is an accessible tool for understanding river flow dynamics and processes at the same scale as experienced by fish. In SHR projects, two-dimensional (2D) hydrodynamic modelling allows testing of numerous design scenarios thereby reducing implementation uncertainty (Pasternack *et al.*, in press). Past SHR analyses typically employed one-dimensional (1D) models, such as PHABSIM, HEC2 or MIKE11. While 1D models have fewer data needs, they do not capture habitat patterns at reach and sub-reach scales (Crowder and Diplas, 2000). Alternatively, 2D and 3D models make spatially distributed velocity (depth-averaged for 2D) and depth predictions. Many examples of public 2D hydrodynamic models now exist: FESWMS (Froehlich, 1989), RMA2 (Donnell *et al.*, 2001), TELEMAC (Galland *et al.*, 1991; Hervouet, 2000; Hervouet and Bates, 2000) and RIVER2D (Steffler and Blackburn, 2002). A code capable of modelling subcritical-supercritical transitions, wetting and drying and steady and unsteady flows is suggested. Academic (e.g. SSIIM: Olsen, 2003) and commercial 3D models exist, but they are very costly to field validate and remain largely untested in restoration practice (with a few exceptions, e.g. Swindale, 1999). In gravel-bed rivers, 3D models are frequently being used in scientific geomorphic investigations (Lane *et al.*, 1999; Parsons, 2002) and may in the future be suitable for application in restoration practice. However, a number of methodological issues, including assessing credibility of model simulations (Hardy *et al.*, 2003), accurately specifying model boundary conditions and handling complex bed topography variations (Lane *et al.*, 1999) suggest their application in restoration may be premature.

A realistic discretization of the model domain is critical to achieving accurate model results (French and Clifford, 2000). Discretization of the modelling domain is typically done by creating a computational mesh in place of the DEM. The quality of a mesh is highly dependent on two factors: (1) DEM quality and (2) mesh resolution. DEM quality is controlled in DEM development; whereas mesh resolution is controlled by node spacing and element size. Models allowing irregular node spacing permit finer-scale mesh discretization (i.e. tight node spacing ≈0.20 m to 0.75 m) around topographically complex areas and coarse-scale mesh discretization (relaxed node spacing ≈0.75 m to 5.0 m) around less complex topography. Tighter mesh resolution can more accurately represent the bathymetry and produce better hydrodynamic model results. However, as node spacing decreases, mesh resolution and computing time increase (refer to: Hardy *et al.*, 1999). Model results should be validated with field data before their use in designs (Bates *et al.*, 1998). Though, field observations have their own sources of error that should also be evaluated.

3.2.3 Sediment entrainment modelling

The longevity of a SHR project depends in large part on the fate of spawning gravels. A channel bed which remains immobile over time typically leads to deteriorated spawning habitat as organics and fines fill interstitial pore-spaces and dissolved oxygen and permeability decline (Chapman, 1988). Even though redd construction itself can clean and mobilize bed material locally (Hassan *et al.*, 2002), gravel movement during peak flows is invaluable to flush fines from spawning beds, replenish spawning gravels and maintain substrate suitability for spawning (Gilvear, 1999). Hence, at least some analysis of the flow conditions under which to expect sediment entrainment is warranted.

A well-accepted approach to predicting sediment entrainment is to compare model-predicted shear stresses to the critical shear stress for entrainment of specified gravel grain sizes. From 2D hydrodynamic model results depth averaged velocity can be used to calculate shear stress on a node by node basis (Wilcock, 1996). Critical shear stress can be estimated using field data, Shields' incipient motion criterion (Garde and Raju, 1985), and Einstein's log velocity profile equation (see Pasternack *et al.*, in press for detail). The ratio of model predicted velocity to critical velocity defines a sediment mobility index (SMI). Sediment entrainment prediction alone is a meaningful indicator of local scour. A variety of more sophisticated techniques for estimating entrainment and transport rates exist; however, sediment transport estimates can vary over orders of magnitude depending on formulae employed and boundary conditions assumed (Gomez and Church, 1989). Wilcock (2001) proposed a "practical" method (that could have utility in SHR) for estimating transport rates that relies on minimizing such errors by calibrating transport formulae against a limited number of observations. Unfortunately, sediment transport observations are frequently nonexistent for SHR projects. The few examples of mobile bed hydrodynamic models (i.e. bed adjusted iteratively in relationship to predicted transport rates) that do exist are still in developmental stages and are primarily only suitable for sand-bedded rivers (e.g. CH3D-SED: Gessler *et al.*, 1999).

3.2.4 Habitat suitability modelling

A quantitative prediction of habitat quality is a key design and assessment tool and readily available for SHR. The most widely employed conceptual model used to explain abiotic-biotic linkages and habitat suitability is the instream flow incremental methodology (IFIM), which employs the PHABSIM 1D model (Bovee, 1996). PHABSIM relies on cross-sectionally and reach-averaged estimates of velocities and depth to assess usable habitat area, but not at a scale relevant to individual fish (Leclerc *et al.*, 1994). Leclerc *et al.* (1995a) introduced a 2D version that resolves predictions of habitat quality at the scale that fish experience it. Pasternack *et al.* (in press) and Wheaton *et al.* (2004) employed a similar approach to assess a SHR project for two separate projects on the Mokelumne River, California. All of the above methods rely on habitat suitability curves (HSC), which are commonly used in aquatic biology (Armour and Taylor, 1991). In such an approach, normalized habitat suitability curves for water depth, velocity and substrate size are developed (refer to Section 3.3.2). The HSCs are then combined into a single global habitat suitability index (GHSI). GHSI can be computed on a node-by-node basis from 2D model results to predict patterns of spawning habitat quality for use in assessment or design. GHSI values range from 0 to 1, with 1 representing the most optimal spawning habitat and 0 indicating non-habitat. GHSI is further subjectively classed as poor (0–0.1), low (0.1–0.4), medium (0.4–0.7) and high (0.7–1.0) quality habitat (Leclerc *et al.*, 1995b).

3.3 Data collection mode

The data collection mode includes a combination of desk-top studies, field campaigns and data analyses. For convenience, we segregate data collection activities into mapping, habitat, bed material and flow.

3.3.1 Mapping data collection

The conceptualization and modelling modes each have specific mapping requirements across a variety of scales. A coarse-scale map (e.g. 1 : 250,000) and DEM (5–30 m contours) of the catchment quantifies basin area, total relief, longitudinal profile, valley type, and channel network pattern. Landscape-scale maps (e.g. 1 : 24,000 or 1 : 63,000) should be used to segregate sub basins into landscape units (e.g. floodplain, hillslope, alluvial fan, valley), identify land use, soils, geology, vegetative cover and assess the role of valley confinement on fluvial processes. Longitudinal profiles of channel thalweg and water surface elevation surveyed throughout the entire length of spawning reaches are invaluable for choosing project reaches (Figure 4). Finally, the hydrodynamic modelling sub-mode requires, a

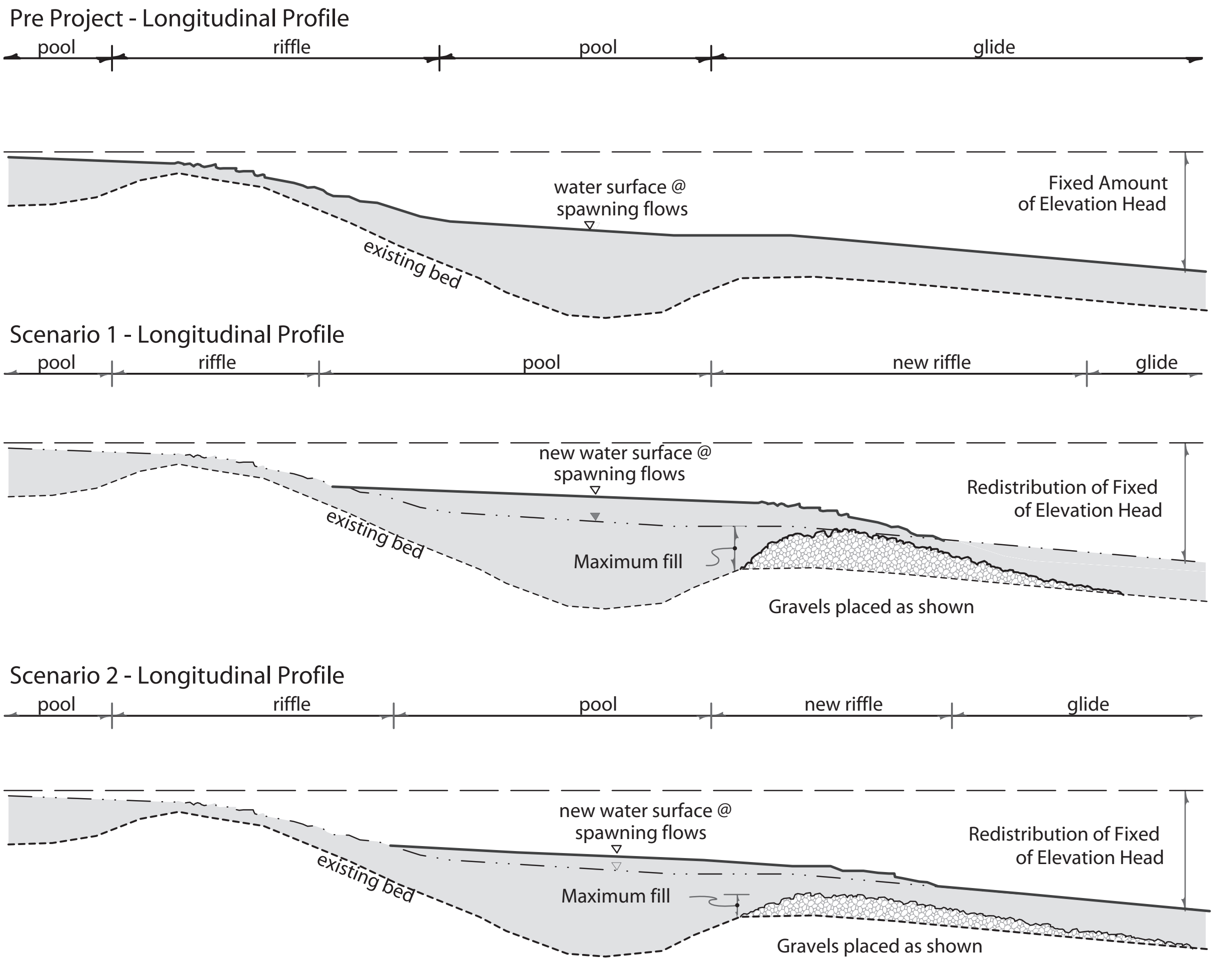

Figure 4 Concept of finite elevation head. The maximum fill depth at the upstream end of a spawning bed enhancement project is the critical control for how much new spawning habitat is created and how much existing spawning habitat is deteriorated upstream from backwater effects. In the pre-project condition, the existing upstream riffle provides high quality spawning habitat but the glide downstream provides poor quality spawning habitat. In scenario one, gravel is placed in the glide to decrease depths and increase velocities; thereby creating optimal spawning habitat over much of the old glide but also inducing a backwater effect on the upstream riffle and deteriorating spawning habitat quality. In scenario two, the maximum fill depth is lower and the trade-off between backwater effect on the upstream riffle and creation of high quality spawning habitat is optimized.

detailed topographic survey (>0.75 point per m^2) using a total station or real-time kinematic Global Positioning System (rtkGPS) and control network tied to a known coordinate system. Lidar technology (refer to: French, 2003) and aerial or close range photogrammetric methods (refer to: Lane *et al.*, 2000) are becoming increasingly popular. If Lidar or photogrammetric methods can produce topographic data of similar resolution, they may be appropriate. However, in a comparison to high resolution rtkGPS and digital aerial photogrammetric surveys of the same reaches, Brasington *et al.* (2003) concluded that data precision and accuracy were lower than traditional ground topographic surveys.

Detailed topographic surveying provides abundantly more useful data than standard cross sections and longitudinal profiles alone. In-channel features should be surveyed with adequate resolution to capture grade breaks and bedforms comprising roughness elements. Stratified point spacing (as opposed to random or uniform) in quasi-systematic manner can be used to obtain high quality data (Brasington *et al.*, 2000). High point density (>3 points per m^2) is used in topographically complex areas (bedrock outcroppings, channel margins) and relaxed point density (>0.5 points per m^2) is used in topographically uniform areas (floodplain, plane bed). At the reach scale, a 15-cm contour interval, 1 : 250 scale mapping, can serve as a "rule of thumb" for resolving geomorphic units, which could have significant influence on two dimensional flow paths. For high-flow modelling, it is helpful to extend surveying out of the channel to include the inundation area of at least over-bank flows with decadal recurrence intervals. Surveying of trees, hardscape, fencing, travel paths, drainage features and utilities is also useful for design purposes. Topographic surveys are often misperceived as too expensive for restoration projects. Once control networks are established, simple reach surveys can be performed by two persons in one day and even complicated reaches rarely take more than a week (Brasington *et al.*, 2000).

3.3.2 Habitat data collection

Physical habitat data collection includes (1) habitat mapping (2) redd surveys and (3) habitat suitability curve (HSC) development. General habitat mapping can be performed by drawing field sketches over topographic surveys, which segregate the channel corridor into habitat types (e.g. riffles, pools, backwaters, glides, etc.). A multi-scalar, geomorphic based approach to mapping habitat is recommended and many exist (e.g. Frothingham *et al.*, 2002; Newson *et al.*, 1998; Thomson *et al.*, 2001). Weekly redd surveys are conducted throughout the duration of the spawning season. Merz and Setka (in press) suggest surveying location by dGPS and measuring depths, velocities, grain sizes, dissolved oxygen content and temperatures at redds soon after spawning and during flow conditions similar to those present at the onset of spawning.

Although many physical, physiological and ecological factors influence spawning site selection, those shown to account for much of the variability include depth, velocity, water temperature, and substrate quality (Knapp and Preisler, 1999). HSCs should be constructed from the distributions of these data for the particular species of interest and preferably from the specific river where SHR is proposed (Hardy and Addley, 2001). Since these measurements are made after redd construction, they are not a true measure of those present when the female selected the site for spawning, so measurements can either be averaged over a range of points in and around the nest or taken at a point just upstream of the nest thought to be characteristic of the pre-redd hydraulic conditions (Merz and Setka, in press). Redd surveys can be overlaid on GHSI model results (Section 3.2.4) to test the predictive capability of HSC. Where HSCs are inadequate to explain variability in spawning patterns, other methods such as Kondolf's (2000a) nine-step method for assessing spawning gravel quality may be used.

3.3.3 Bed material data collection

Habitat quality, sediment entrainment and hydrodynamics are all dependent on the composition and arrangement of substrate. Modelling hydrodynamics relies on estimates of roughness, which are related to substrate composition and bedform shape (Lane *et al.*, 1999). A surface grain size distribution obtained by Wolman pebble counts quantifies percentile classes if such distributions are approximately normal (Bunte and Abt, 2001). If further spatial segregation of bed sediments is deemed necessary, facies maps can be drawn in concert with Wolman pebble counts stratified by substrate class (facies). Frozen sediment core samples can be obtained at random locations within specific sediment facies to characterize subsurface sediments (Bunte and Abt, 2001). If a sediment budget is being prepared, bedload and suspended load measurements over a range of discharges are desirable (McLean and Church, 1999). For monitoring, gravel tracer studies can be used to track the fate of placed spawning gravels (Wilcock *et al.*, 1996).

3.3.4 Flow data collection

Three types of flow data are needed for SHR projects. First, historical flow records characterize flow regime, with particular attention towards spawning and flood flows. If pre-regulation flow records exist, insightful comparisons of pre- and post-regulation flow regimes can help illuminate the impacts of flow regulation on hydrologic and geomorphic processes (e.g. Richter *et al.*, 1996). Second, rating curves of stage versus discharge spanning minimum releases to flood flows are needed at the downstream boundary of each hydrodynamic modelling reach. Finally, measurements of water depth and velocity are needed to validate hydrodynamic model results (Pasternack *et al.*, in press), estimate bed shear stresses (Dietrich and Whiting, 1989), verify discharges against gage readings, estimate hydrodynamic model parameters such as eddy viscosity (Fischer *et al.*, 1979) and assess appropriate spawning velocities for target species (Section 3.3.2). As hydrodynamic processes vary in time and space, careful consideration should be given to the spatial and temporal resolution at which such measurements are performed (Lane *et al.*, 1998).

3.4 Scientific exploration mode

Given that SHIRA is modular and that SHR projects can be viewed as controlled experiments, the scientific exploration mode provides the opportunity to continually improve SHIRA in three distinct ways. First, individual scientific concepts may have deficiencies that become apparent when rigorously tested during practical application. It is important to make a thorough inventory of sources of uncertainty and analysis of quantifiable uncertainty to either improve or replace the concept. Second, as new technologies become available, they may be evaluated for use in SHIRA. Third, scientific experiments may be needed to determine how to incorporate new ideas into the design and planning process. For example, in-channel features such as LWD and hydraulic jumps are known to be important for salmonids (Hilderbrand *et al.*, 1998), yet science-based approaches for including these in design still need development. Experimental findings should be reported in the peer-reviewed literature.

4 SHIRA phases – a practical implementation process

4.1 Phases in brief

Whereas modes are tools used at any time during SHR projects, phases represent a chronological sequence of steps (Figure 2). Aside from design, the phases in SHIRA are similar to those presented in other approaches (e.g. FISRWG, 1998) and are hence only briefly summarized here (Table 2). During the preliminary planning phase, goals, sites, and support are sought within a basin-scale context (e.g. Brookes and Shields, 1996; FISRWG, 1998; NRC, 1992). Site selection should be carefully chosen with

Table 2 Summary of key tasks performed in each phase of SHIRA. The modes used are abbreviated as follows: DCM: data collection mode; MM: modelling mode; CM: conceptualization mode; and SEM: scientific exploration mode.

Phase	Key tasks	Mode(s) used
Phase one: Preliminary planning	Baseline data collection performed	DCM
	Historical flow analysis	DCM
	Compile historical annual redd surveys and HSC	DCM
	Historical geomorphic analysis	DCM
	Historical context summarized	DCM, CM
	Basin context explicitly recognized (watershed assessment)	DCM, CM
	Problem definition and development of explicit conceptual model	CM
	State objectives, select monitoring indicators and outline monitoring timeline	CM
	Explicit recognition of how SHR project fits in basin management plan	CM
	Feedback and support from stakeholders	CM
	Project constraints identified (e.g. budget, construction access, construction timing, gravel availability)	DCM, CM
	Site selection	CM, MM?
Phase Two: Pre-project	Detailed topographic survey and habitat mapping	DCM
	Bed material characterization and collect flow validation data	DCM
	Build and run hydrodynamic, habitat suitability and sediment entrainment models	MM
	Validate and refine model until satisfactory results	MM
Phase Three: Design	See Section 4.2	CM, MM
Phase Four: Final design selection	See Section 4.2.4	CM, MM
Phase Five: Construction	Designer to communicate key goals and design elements to contractor in pre-construction meeting (including: construction access, grave handling and cleanliness, construction staging areas, identification of sensitive areas and potential hazards)	NA
	Construction staking to be provided to delineate boundaries, fill elevations, etc.	NA
	Spot grade checking to ensure finish elevations match design	DCM
	Construction observation for (clarifications, modifications and reality check)	DCM
Phase Six: Post project assessment	Detailed topographic survey and habitat mapping	DCM
	Bed material characterization and collect flow validation data	DCM
	Build and run hydrodynamic, habitat suitability and sediment entrainment models	MM
	Validate and refine model until satisfactory results	MM
	Prepare first post project appraisal	CM
Phase Seven: Long term monitoring and adaptive management	Carry out long term monitoring of pre-defined indicators and track morphological change, habitat utilization.	DCM
	Adaptive management	SEM, CM
	Publish all data as part of an information inventory	DCM, SEM

respect to the river's longitudinal profile with ample consideration of future SHR projects as well as current spawning habitat sites (Figure 4). To ensure value in later monitoring and assessment, it is crucial to establish a hypothesis-driven experimental purpose along with applied goals. Next, the pre-project phase thoroughly documents site specific baseline conditions. This begins with an intensive field campaign at least one year prior to anticipated construction and is concluded with detailed modelling analyses. In Section 4.2, the design phase is discussed more specifically. Months can be spent designing minute details of individual design scenarios. However, when construction commences, there are limits to the detail an excavator or front-end loader with a 4–6 m^3 bucket can achieve. Given these constraints, construction should focus on general design intent first and specific details second. Phase six provides the first post project appraisal (PPA) with special attention towards how well the construction matched the final design. Downs and Kondolf (2002) outline an eight-part PPA process which includes: success criteria, baseline surveys, design rationale, design drawings, post-project monitoring survey, supplementary historical data, and secondary analytical procedures. The final phase is then comprised of three parts: (1) long-term monitoring (Brookes and Shields, 1996; FISRWG, 1998), (2) adaptive management (Walters, 1986) and (3) information inventory. Numerous sources are available for developing monitoring protocols (Kondolf, 1995a; Newson, 2002).

4.2 Design

Design in SHIRA is segregated into a development phase and a final selection phase. Design development has three parts: (1) conceptual design formulation, (2) detailed design development, and (3) design testing. Design is a creative process, and its real-world utility depends on objective testing of multiple scenarios as opposed to development of a single design. In the same way Chamberlin (1890) advocates multiple working hypothesis, multiple design scenarios can include both those that designers hypothesize as appropriate solutions and "null" designs. As an example, multiple conceptual models have been proposed to explain why pool-riffle sequences tend to maintain themselves: Keller's (1971) original 'velocity reversal hypothesis', secondary flow cell convergence and divergence (Clifford and Richards, 1992) and Thompson's (1999) 'revised velocity reversal hypothesis'. Although none of these conceptual models have been proven, nor is it likely that there is a single explanation for the self-maintenance of pool-riffle sequences, they can provide a reasonable basis for design. Thompson *et al.* (2001, 1999) proposed that pool-riffle maintenance was sometimes due to width constrictions upstream of pools and width expansions upstream of riffles (which, is thought to concentrate flow through the pools and allow it to dissipate out across a riffle). Thus, a hypothesized design scenario may aim to constrain channel width in the pools and allow width to expand across riffles. The "null" design scenario would propose the opposite (constant channel width or width constriction in riffle). Hydrodynamic and SMI model results of the hypothesized and null design scenarios at flood stages can indicate whether the conceptual model indeed explains the desired process. All scenarios are designed within the specific SHR project constraints (i.e. site location, quantity of gravel available, construction access, construction equipment).

4.2.1 Conceptual design formulation

Numerous design scenarios can be formulated conceptually by drawing "form-process sketches" of designs over existing channel topography, habitat and geomorphic maps. A simple conceptual planform sketch delineating where gravel will be placed to create the desired channel forms should be drawn. More importantly, the hydrogeomorphic processes and related ecological functions hypothesized to be produced by such a design scenario are added to the map. The conceptual "form-process sketch" should document a designers' ideas for a proposed design and how they hypothesize that design will function. For example, it may be proposed to convert an incised glide with homogenized depths and velocities into a pool-riffle. Because of the past emphasis on cross-sections, little geomorphic theory exists at the sub-reach scale to constrain habitat-scale riffle morphology. Natural rivers show wide diversity (Montgomery and Bolton, 2003), thereby offering latitude in design details. Until DEM-based fluvial geomorphic theory is developed to address this critical gap in understanding, designers should draw on hydrodynamic patterns and processes known from experience or analogue conditions for designing sub-reach and hydraulic-unit scale features. Hence, the designer should not become overly attached to any single design hypothesis (Schumm, 1991).

4.2.2 Detailed design development

Detailed design development converts the conceptual design into a DEM. While many applications exist for building DEMs, computer-assisted-drafting (CAD) programs are the design industry-standard, and more efficient for drafting grading plans. DEM data can be exported to a hydrodynamic modelling interface. DEM data can be exported to a hydrodynamic modelling interface. CAD allows easy calculation of fill volumes and extraction of long profiles and cross sections from a DEM. Design gravel sizes should be specified using a combination of HSCs, literature reports of gravel sizes (e.g. Kondolf and Wolman, 1993) and physical constraints from the gravel supplier.

4.2.3 Design testing

Design testing in SHIRA uses the modelling mode to evaluate design scenarios relative to flow structure, habitat, geomorphic process, and sediment entrainment criteria. While true model validation of design scenarios is not possible, model results are directly comparable because model elements are pre-specified (Pasternack *et al.*, in press). The primary source of error in 2D modelling is DEM inaccuracy from poor field data (French and Clifford, 2000), which only plays a minor role in a design DEM. Yet, the fundamental limitations of 2D models (e.g. inability to resolve vertical components due to depth averaging) and the nature of modelling uncertainties must be understood with respect to the ability of model results to test hypotheses. However valid a design hypothesis involving the importance of secondary flow cells with a vertical component may be, a 2D model cannot be used to assess this hypothesis (Lane *et al.*, 1999). Spatial predictions of GHSI should be used to test for design efficiency (volume of gravel added per area) and habitat patch size. A habitat patch must be larger than a single redd ($\sim$1–3 m^2) to be of spawning value. The sediment entrainment predictions can be used at spawning flows to design against potential scour and at high flows to verify or reject the validity of the designers' geomorphic process inferences made in the conceptual design formulation. In individual projects, designers will have to decide if the models discussed here are adequate to objectively test hypothesized processes resulting from design scenarios. If not, other models may be deployed or the inability to test specific aspects of design hypothesis should be explicitly reported.

4.2.4 Phase 4: final design selection

After multiple design scenarios have been developed and tested, assessment and comparisons should be made. Although the outcome of this process is normally the selection of a single design, it should be recognized that there is no single correct answer (Schumm, 1991) and that the analyses might suggest that nothing should be done. It is better to arrive at this conclusion before the expense and impact of construction are realized rather than during a post project appraisal. Findings should be presented to experts and managers to get feedback and direction before refining the final design. The final design scenario may simply be the perceived best scenario from the design phase or a combination of scenarios. Alternately, it may be the one yielding the best test of an experimental hypothesis. Ultimately, a transparent decision should be made on the basis of the early analyses. Once a final design scenario is refined, model results should be solidified and construction documents prepared. Construction document requirements will vary according to the project contractor and regulatory agencies involved. At a minimum, construction documents should include pre-project topography and a grading plan depicting configuration of placed gravel fills and highlighting critical design elements. Construction documents should convey all information necessary for a general engineering contractor to read them. If a competitive bidding process is being used to select a contractor, it may be helpful to have plans reviewed by a professional engineer before distribution.

5 Discussion – other design considerations

Restoration of regulated rivers is by definition impossible without dam removal. Dam removal has grown in popularity for the restoration of native fisheries and geomorphic processes (Doyle and Harbor, 2003). However, it is expensive and usually only proposed for small dams where there exists a clear alternative for water storage and flood control (Bednarek, 2001). On many larger salmon rivers, dam removal may not be a realistic option (Graf, 2001). However, improvement of certain geomorphic and ecologic functions on regulated rivers through rehabilitation efforts like SHR may be feasible. SHIRA can provide a framework within which SHR efforts may be effectively carried out.

5.1 Importance of habitat heterogeneity

One logical way to develop SHR design scenarios using a 2D hydrodynamic model and GHSI results, is to produce designs optimizing bed configuration to achieve the maximum area of GHSI-defined optimal habitat. This logic has guided past efforts at SHR (Kondolf *et al.*, 1996). From our experience, optimization with GHSI alone at a single discharge may produce relatively homogenous flat riffles. GHSI provides valuable insight into potential spawning habitat preferences, but many factors influencing spawning are simply not represented (Knapp and Preisler, 1999). While optimal spawning habitat is generally found in riffles, proximity of optimal spawning habitat to pools, LWD, boulder clusters, flow separations (eddies) and overhanging cover can be equally important to spawners. Such structural elements allow the female to quickly seek refuge from predation or rest while still allowing defence of her redd (McPhee and Quinn, 1998; Merz, 2001a). Another problem arises in designs based entirely on GHSI at a single flow. Spawning flows may fluctuate with downstream water demand. A flat riffle designed for optimal GHSI habitat at a single flow could potentially produce poor quality habitat over the entire homogenous riffle at a different spawning flow. Topographically diverse riffles are more likely to provide a range of GHSI-defined quality habitats over variable flows. Habitat heterogeneity should afford multiple habitat functions to different species. Finally, habitat quantity should be balanced with geomorphic sustainability, and the latter rarely suggests a long, flat riffle.

Incorporating complex features into a design can improve the quality of habitat beyond the predictive capability of current numerical models. Numerical models can reduce some uncertainties in design outcomes but need to be combined with conceptual models and practical limitations of construction to achieve spatial heterogeneity. Hydraulic structures can be used to add habitat heterogeneity and fluvial complexity in otherwise homogenized flow conditions (Hilderbrand *et al.*, 1998; Jeffries, 2002). In a true channel restoration, hydraulic structures, such as boulder clusters or LWD, may not be justified on the basis of historical evidence in reaches where SHR is now proposed. However, since SHR is intended to improve certain ecologic and geomorphic functions that are now lacking, the use of structural elements may be justified. This is probably only appropriate if the inferred processes and benefits associated from such structures can be modelled or tested in the design phase. LWD is very difficult to model in 2D (Pasternack *et al.*, in press), while boulders are manageable (Crowder and Diplas, 2000). Model results can be used to infer whether structures produce desired hydrogeomorphic processes and ecologic functions. However, model results cannot predict the rate at which boulder clusters may induce scour or rates at which LWD will break down or blow out. Thus, hydraulic structures may provide benefits in the form of habitat heterogeneity, but considerable uncertainty in the channel response to these features must be accepted.

5.2 Integration of conceptual features into designs

A number of empirical studies and general observations of spawning activity have led to conceptual models of processes that presently cannot be numerically modelled. Is the inclusion of such conceptual models warranted in design development? For example, chinook salmon (*Oncorhynchus tshawytscha*) are thought to preferentially spawn where hyporheic flow occurs (Geist, 2000; Vronskiy, 1972). One example of bedforms thought to promote hyporheic flow is pool-exit slopes. Water is vertically constricted through a pool exit slope and then spreads over a shallow riffle, characterized by decreased depth and increased velocity. The head gradient induced in this zone can promote downwelling through permeable spawning gravels. Lisle and Lewis (1992) explain that even if eggs incubate successfully, alevins still need connected pore spaces to emerge. Hyporheic flow of water through the gravels is thought to maintain such connected pore spaces by flushing fines and increasing dissolved oxygen values critical to egg survival. Although most hydrodynamic models are not coupled to hyporheic flow models, and GHSI does not account for downwelling at pool-exit slopes, the process-inference may well justify the use of pool-exit slopes in designs.

5.3 Channel stability

Channel stasis is not an appropriate goal of SHR projects (Kondolf, 2000b). Even in severely regulated rivers that rarely experience shear stresses over a "critical threshold", Paintal (1971) shows that sediment transport will occur and can eventually yield significant change. In natural rivers spawning gravels turn over and bedforms are re-supplied from upstream. Overton (1984) noticed that some spawning sites persisted from year to year whereas others (40 to 80%) were transitory. Thus, a mix of transitory and stable bedforms may be appropriate for SHR. Montgomery *et al.* (1999) concluded that bed scour depths must constrain spawning distributions because population survival would be unsustainable if scour depths consistently exceeded egg burial depths during the incubation period. To further confuse matters, channel locations, which experience active bedload transport, may in some cases support topographically stable reaches (DeVries, 2002). Relating channel stability and sediment transport to spawning habitat is an active area of research with considerable uncertainty due to both the variability in processes and our lack of knowledge (Montgomery and Bolton, 2003). As it is difficult to draw generic design conclusions about channel stability, designers that rely on a process-based approach can grapple with the applicability of stability concepts to their sites. Shields *et al.* (2003) offer some hydraulic engineering design tools for considering channel stability in channel reconstruction that may have some utility in specific SHR contexts. We discourage the expectation that an enhanced gravel bed should necessarily remain exactly as it was placed.

5.4 Limitations

The largest limitation of SHR is that it is an active-approach to rehabilitation focused at the reach scale over inter-annual time scales. SHR may not be sustainable at longer time scales unless supporting geomorphic processes are achieved through larger spatial and temporal scale watershed-based restoration or management. Project lifetime remains the largest unknown. The assumption is that SHIRA is used as part of a larger watershed scale restoration program, but the reality may be that funding is only spent on piecemeal individual spawning bed enhancement projects without appropriate long term or large scale planning. If the latter is the case, SHIRA will likely provide cost-effective short-term benefits that may diminish with time in the absence of periodic maintenance or gravel augmentation. Conversely, gravel augmentation is unlikely to produce or sustain target habitat until larger-scale geomorphic processes have been recovered (may take decades to centuries). Pulse-flows may provide a mechanism in regulated rivers by which certain ecologic and hydrogeomorphic functions can be achieved (Andrews and Nankervis, 1995). Whiting (2002) suggests partitioning the annual hydrograph into certain functions in which the flow magnitude determines the function (e.g. pool scour, riffle-cleansing, riffle mobilization will require different magnitude flows). However, flow adjustments to improve flow-sensitive habitat characteristics are often difficult to obtain because of pre-existing water allocation. Similarly, if regular gravel augmentation is not done to alleviate coarse-grained sediment deficits, spawning bed enhancement projects will likely not last. Thus, it is apparent that a combination of gravel augmentation, spawning bed enhancement and flow augmentation will be required to achieve restoration of the full array of spatial and temporal scales of biological and geomorphic riverine processes.

Individual river systems may provide design challenges currently not explicitly outlined in SHIRA. For example, when applying SHIRA on the Mokelumne River, water quality has not been shown to be problematic for salmonids (Merz, 2001b). In rivers where water quality is a limiting factor, it may be appropriate to modify SHIRA to include water quality assessment capabilities (see Herricks, 1996 for examples). SHIRA itself can be adaptively managed and changed by practitioners as needed to include new sub-modes that address future shortcomings.

6 Conclusion

The three most common types of spawning habitat rehabilitation projects are gravel augmentation, hydraulic structure placement and spawning bed enhancement. SHIRA provides a framework and detailed design methods for undertaking spawning bed enhancement and hydraulic structure placement forms of SHR. The approach uses four separate modes as tools throughout the course of sequential project phases. The ideas embodied in the components of SHIRA are not necessarily new or conceptually difficult to understand, and this may be what makes its application useful. Still, SHIRA is a departure from many restoration approaches in that more emphasis is placed on design. While clarifying *what* to do in restoration projects plays an important role in refocusing restoration efforts, it is also important for the scientific community to help practitioners figure out *how* to apply the findings of our research. As we have applied SHIRA on three projects to date (with three others underway), we have demonstrated SHIRA implementation is possible, but not free of problems (Wheaton, 2003). No approach should ever become a substitute for creativity and dynamic interaction with others during the design process. From a scientific perspective, implementation of habitat rehabilitation projects provides unique opportunities to test hypotheses on river system processes. The prospect of coupling future ecosystem-rehabilitation efforts with scientific studies is an exciting opportunity for practitioners and scientists to collaborate and gain improved understanding of riverine ecosystems.

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List of Acronyms and Abbreviations

1D	one dimensional
2D	two dimensional
3D	three dimensional
CAD	computer assisted drafting
DEM	digital elevation model
dGPS	differential global positioning system
GHSI	global habitat suitability index
HSC	habitat suitability curve
IFIM	instream flow incremental methodology
LWD	large woody debris
PPA	post project appraisal
rtkGPS	real time kinematic global positioning system
SHR	spawning habitat rehabilitation
SHIRA	spawning habitat integrated rehabilitation approach
SMI	sediment mobility index
TIN	triangular irregular network

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