Use of habitat heterogeneity in salmonid spawning habitat rehabilitation design

J.M. Wheaton*, G.B. Pasternack
Department of Land, Air and Water Resources, University of California at Davis, Davis, California, U.S.A.
**currently: School of Geography, University of Southampton, Southampton, U.K: Joe.Wheaton@soton.ac.uk.*

J.E. Merz
Department of Wildlife, Fish and Conservation Biology, University of California at Davis, Davis, California, U.S.A.

ABSTRACT: A shortage of salmonid spawning habitat on dammed and regulated rivers has led to the popularity of spawning habitat rehabilitation projects. Habitat heterogeneity is thought to be an important feature of aquatic ecosystems, but specific metrics for design and assessment are lacking. In August 2002, ~ 2,786 metric tons of spawning gravels and 7 large boulders were placed in a 155 meter reach on the lower Mokelumne River, California, USA. Habitat heterogeneity was incorporated into the design as part of a spawning habitat integrated rehabilitation approach (SHIRA) developed by the authors. A mix of conceptual and numerical models (2D hydrodynamic with habitat suitability and sediment entrainment submodels) were used to test the effectiveness of design scenarios. Although optimal spawning habitat as defined by habitat suitability models is generally found in riffles, proximity of habitat to structural cover (pools, large woody debris, boulder clusters and overhanging vegetation) and hydrodynamic shear zones provide equally important refuge from predation and resting zones for energy conservation. The increased heterogeneity appeared highly effective in terms of redd utilization with 70 redds located in close proximity to 93% of the available structural cover, and 42 redds located in close proximity to 90% of the available shear zone refugia. Partial results emphasizing habitat heterogeneity availability and utilization metrics are presented to illustrate their potential in rehabilitation design and assessment.

1 INTRODUCTION

In both the ecology and geomorphology literature, the importance of habitat heterogeneity is usually presumed to positively influence biodiversity (NRC 1992; Palmer et al. 1997); but habitat heterogeneity can manifest benefits in terms of specific ecologic functions as well (Wheaton et al. 2004b). In a review of 85 papers on habitat heterogeneity in terrestrial ecosystems from 1960-2003, Tews et al. (2004) found 85% reported a positive correlation between species diversity and habitat heterogeneity; but caution that metrics for measuring species and structural diversity are inconsistently defined and highly scale-dependent. This highlights a vague distinction between the presumed benefits of habitat heterogeneity and the impacts of habitat fragmentation. The notion of the importance of habitat heterogeneity is also well engrained in the habitat restoration community (Pretty et al. 2003), but how this is achieved in practice remains ambiguous. In many rivers of North America and Europe, declines in salmonid populations have been partially attributed to elimination, degradation and homogenization of physical habitat (Cowx & Welcomme 1998; Hendry et al. 2003; Nehlsen et al. 1991). This has prompted the allocation of millions of euros, dollars and pounds towards spawning habitat rehabilitation (SHR) efforts (Kondolf 2000; Nijland & Cals 2000). Wheaton et al. (2004b) segregate SHR into a passive approach: gravel augmentation; and two active approaches: hydraulic structure placement (e.g. large woody debris, boulders, deflectors) and spawning bed enhancement (e.g. riffle construction). Hydraulic structures are frequently intended in habitat rehabilitation to increase heterogeneity, with intended benefits to juvenile lifestages and macroinvertebrates (Muotka et al. 2002); but are usually only used in SHR to promote deposition of spawning gravels (Wheaton et al. 2004b). Here, we focus on specific ecological benefits of habitat heterogeneity to spawning salmonids (e.g. Merz 2001). Presumed ecosystem benefits of increased species diversity from habitat heterogeneity are not addressed.

This paper illustrates how habitat heterogeneity can be incorporated to SHR through use of habitat availability metrics in design and their effectiveness assessed through habitat utilization in pre and post project appraisal. A SHR project constructed in August 2002 on the lower Mokelumne River (LMR), California, USA is used as a case study. The SHIRA (spawning habitat integrated rehabilitation approach) framework was used to plan, design, construct and monitor the project; but details of the approach, provided in Wheaton et al. (2004a; 2004b), are not discussed here. The structural features used to provide habitat heterogeneity are themselves microhabitat scale (10^{-1} to 10^{0} m) features but produce heterogeneity over the macrohabitat or morphological-unit scale (10^{0} to 10^{1} m).

2 STUDY SITE

The Mokelumne River of central California drains a 1700 km^2 basin out of the Sierra Nevada westward to the Sacramento-San Joaquin Bay Delta (see Merz 2001). Sixteen major dams or diversions have dramatically altered the LMR's flow regime reducing the two year recurrence interval flow from 164 to 54 cumecs (Pasternack et al. 2004). The dams have blocked the replenishment of spawning gravels to the LMR since 1963. SHR for fall-run chinook salmon (*Oncorhynchus tschawytscha*) is now required as part of dam relicensing on the LMR (FERC 1998). The upper 9.6 km of the LMR is a gravel bed river (surface D_{50} ˜ 45 mm at study reach). The 220 m long study reach is located roughly 4 km downstream of the lowest non-passable reservoir to anadromous fish. The study reach is the site of a 155 m long SHR site designed by the authors, in which ~2786 metric tons of spawning gravels and 7 large boulders were placed in August 2002. The project increased local reach slopes from 0.0015 to 0.0032 by elevating the upper riffle crest roughly 0.5 m, but maintained the same planform geometry and ~30 m channel widths.

3 METHODS

To include habitat heterogeneity in design, we focused on providing high quality spawning habitat in close proximity to a variety of structural features thought to provide specific benefits to salmonids. Wheaton et al. (2004a) demonstrated development and testing of habitat heterogeneity and other design hypothesis for SHR at a separate project roughly 3 km upstream. In the interest of space, the reader is referred to Wheaton et al. (2004b) for a complete description of the SHIRA methodology used in both projects and Wheaton et al. (2004a) for specific details about the FESWMS 2D hydrodynamic model, model validation, Global Habitat Suitability Index (GHSI) submodel, and Sediment Mobility Index (SMI) entrainment submodel used to test design hypotheses and assess pre and post project conditions. Results from representative steady-state simulations using FESWMS and the GHSI spawning habitat suitability submodel at representative spawning flows were used to quantify habitat quality and availability for pre (2001: ~9.34 cumecs) and post (2002: ~7.24 cumecs) project conditions. Metrics of habitat availability for the three different design scenarios developed are not reported here (incidentally the post project metrics are very similar to the final design). Thus, spawning habitat quality was assessed on the basis of depth and velocity habitat suitability curves for fall-run chinook salmon from the LMR and m^2 of availability calculated from GHSI predictions. Utilization of spawning habitat was assessed by counting the number of redds in the different GHSI-defined areas.

Habitat heterogeneity was provided by locating structural features, intended to increase fluvial complexity, in close proximity to spawning habitat. 'Close proximity' was loosely defined based on empirical analysis of proximity to seven types of structural elements with 136 individual redds from the LMR. Structural features were to serve specific ecologic functions without fragmenting habitat. We focused on two types of structural features: those that provide cover and those that produce hydrodynamic shear zones, which in turn generate 'dead zones' or eddies large enough for fish utilization. The importance of structural cover to aquatic fauna is well established (Pretty et al. 2003). Benefits to salmonids include protection from predation, resting, primary production and water temperature regulation (Merz 2001; Hendry et al. 2003). We calculated the availability of structural cover in terms of area (in m^2) and a count of distinct units of bank vegetation, LWD complexes, boulder clusters and deep pools (Bisson et al. 1981). The availability of shear zones was also calculated in terms of area and a count of distinct units depicted within 2D hydrodynamic model simulations. The presence of hydrodynamic shear zones were attributed to one of four surveyed features: bank irregularities, LWD complexes, boulder clusters and bedforms. Utilization was then assumed to be indicated by the number of redds (acquired from weekly redd surveys with a dGPS) in close proximity to distinct structural units. 'Close' proximity varied between 1 and 10 m and individual redds often utilized more than one structural unit. Anecdotal evidence from over 10 years of monitoring on the LMR and weekly site visits during spawning support these assumptions. A GIS was developed to assess the above metrics from a combination of field reconnaissance, detailed topographic surveys, 2D hydrodynamic model results (for shear zones), spawning habitat suitability model results (for habitat quality predictions) and weekly redd surveys (Merz & Setka In Press).

4 RESULTS & DISCUSSION

The availability of pre project (2001) spawning habitat was dominated by low quality habitat (52%) with

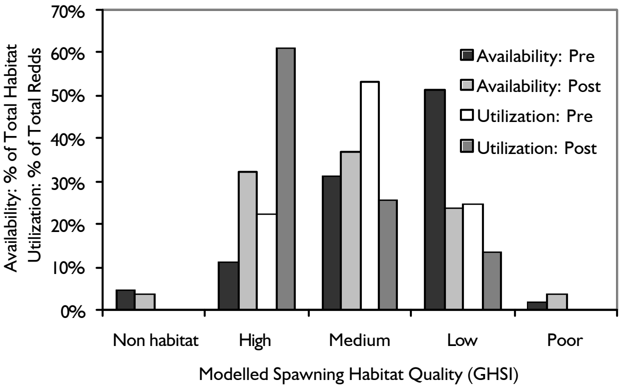

Figure 1. Comparison of pre and post project modeled spawning habitat quality availability and utilization

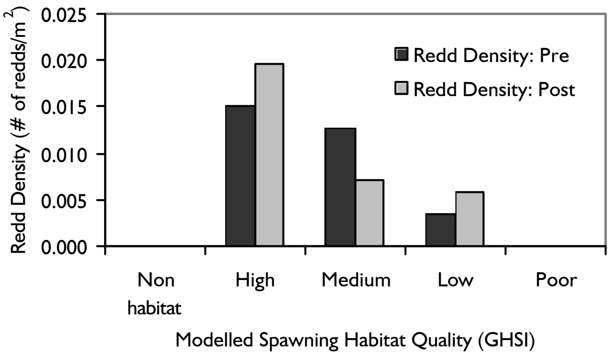

Figure 2. Redd Densities as validation of GHSI model predictions of habitat quality.

a low availability (11%) of high quality spawning habitat (Fig. 1). The best quality spawning habitat was segregated in two distinct zones 100 m apart: an upper 'crossing riffle' and a lower 'island riffle', which together comprised only 26% of the total available habitat. Post project (2002) availability shifted the distribution towards higher quality habitat raising high and medium quality habitats from 11% and 31% respectively to 32% and 37% (Fig. 1). This was accomplished primarily by extending the 'crossing riffle' further downstream and building a central bar extending down to the 'island riffle', which divided the flow and created three distinct small pools. Spawning habitat utilization then shifted from two to five distinct areas comprising 35% of the total study reach.

Although there are strong annual fluctuations in ocean harvest, adult escapement, river spawners and hatchery intake, the total number of redds in the LMR in 2001 and 2002 showed only minor variation with 843 and 826 redds respectively. Similarly, it is difficult and questionable to attribute the modest increase in redds observed at the site from 2001 to 2002 (49 to 59 redds) to the SHR project. However, the patterns of habitat utilization and availability provide a mechanistic explanation of habitat preference that is directly attributable to changes brought about by the SHR project. The predictive capability of the GHSI model is well validated by redd densities, which although higher in 2002 show consistent agreement with the high, medium and low quality habitat predictions (Fig. 2). Further, the GHSI effectively segregates poor and non-habitat (deep pools or dry areas) with no redd utilization experienced in these areas. In 2001, only 22% of the redds were located in high quality habitat and 53% settled for medium quality habitat; a strong reflection of the limited availability of high quality spawning habitat. In 2002 by contrast, 61% were located in high quality habitat and 25% in medium quality habitat; again, a reflection of the increased availability of high quality spawning habitat. On the basis of this analysis alone, the merit of increasing spawning habitat quality is questionable if lesser quality habitat is still used. However, Merz et al. (In Press) have shown increased survival of salmonid embryos from 12 separate SHR projects on the LMR. Hence considerations other than simply providing high quality spawning habitat and utilization are essential.

The SHR project also increased habitat heterogeneity through introduction of more structural cover (from 12 to 21 distinct aerial units) and hydrodynamic shear zones (from 5 to 18 distinct slack water areas). The majority of the existing structural cover was bank vegetation, with a few deep pools (Fig. 3). The increases were provided through placement of three distinct boulder complexes, and placing gravel in the channel to accentuate bank irregularities and promote zones of flow convergence and divergence. In addition two LWD complexes floated in and deposited within the site shortly after construction. In 2001, only 10% of the total study site area provided structural cover utilized by spawners and none of the shear zone refugia was utilized (Fig. 3 and 4). This is most likely because the limited amount of such structural heterogeneity was not in close proximity to the two riffles providing reasonable quality spawning habitat. In 2002, over 23% of the total study area provided structural cover (Fig. 3) and 14% provided shear zone refugia. This increased heterogeneity appeared highly effective in terms of redd utilization (i.e. redd proximity) with 70 redds using 93% of the available structural cover in one or

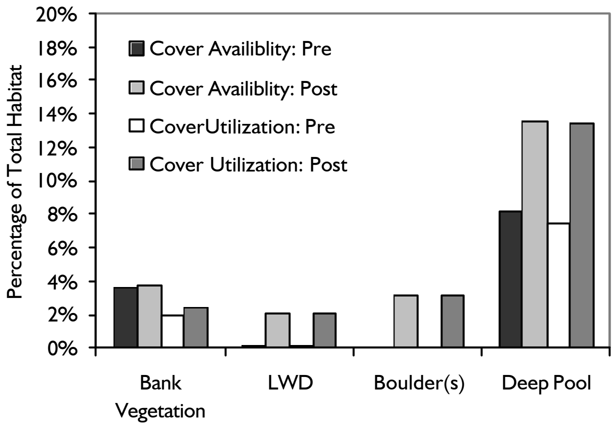

Figure 3. Habitat heterogeneity expressed in terms of structural cover. Comparison of pre and post project availability and utilization.

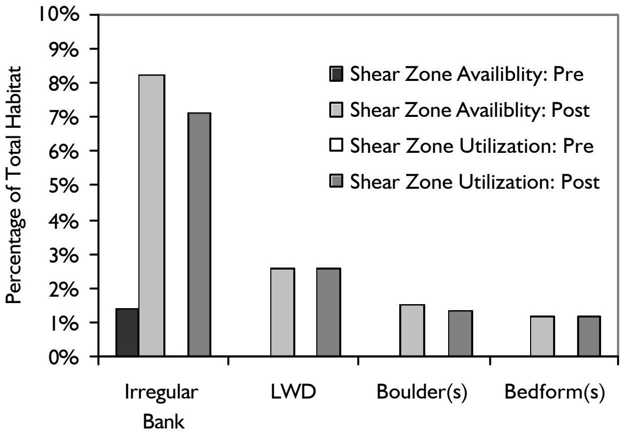

Figure 4. Habitat heterogeneity expressed in terms of shear zone refugia. Comparison of pre and post project availability and utilization.

more ways, and 42 redds using 90% of the available shear zone refugia. Deep pools and irregular banks were the most available and utilized structural cover and shear zones respectively. LWD on the LMR has been reduced from historic levels and the banks are artificially armored with vegetation that has established following the highly regulated flow regime (Merz 2001).

5 CONCLUSION

Although these results highlight the importance of habitat heterogeneity and some potential metrics for expressing it, the dependence of any empirical observations of habitat utilization is intimately tied to habitat availability. None-the-less, these results quantitatively capture ecohydraulic mechanisms (shear zones) and structural features that produce habitat heterogeneity and apparent benefits to salmonids. Thus, the methods and metrics for assessing habitat heterogeneity should be easily transferable to a variety of habitat restoration projects. However, the longevity of techniques used to produce desired processes (in this case shear zones) and structural features (in this case cover) will depend on an adequate consideration (e.g. SHIRA) of sustaining hydro-geomorphic processes and anticipated disturbances.

6 ACKNOWLEDGEMENTS

Financial support for this work was provided by East Bay Municipal Utility District (Research Agreements OOK6046 & 99K3086), the University of California, the US Fish and Wildlife Service (contracting entity for CALFED Bay-Delta Ecosystem Restoration Program: Cooperative Agreement DCN# 113322G003) and a National Fish and Wildlife Federation grant through CALFED (Contract #99-NO6).

REFERENCES

Bisson, P.A., Nielsen, J., Palmason, R.A., & Grove, L.E. 1981. A system of naming habitat types in small streams, with examples of habitat utilization by salmonids during low streamflow, In Armantrout, N.B. (ed.), Acquisition and utilization of aquatic habitat inventory information: American Fisheries Society Western Division.

Cowx, I.G., & Welcomme, R.L. (Eds) 1998. Rehabilitation of Rivers for Fish. Oxford, UK: Fishing News Books.

FERC 1998. Order Approving Settlement Agreement and Amending License. East Bay Municipal Utility District Lower Mokelumne River Hydroelectric Project No. 2916.: Federal Energy Regulatory Commission.

Hendry, K., Cragg-Hine, D., Grady, M.O., Sambrook, H., & Stephen, A. 2003. Management of habitat for rehabilitation and enhancement of salmonid stocks, Fisheries Research, 62: 171-192.

Kondolf, G.M. 2000. Some suggested guidelines for geomorphic aspects of anadromous salmonid habitat restoration proposals, Restoration Ecology, 8(1): 48-56.

Merz, J.E. 2001. Association of fall-run chinook salmon redds with woody debris in the lower Mokelumne River, California, California Fish and Game, 87(2): 51-60.

Merz, J.E., & Setka, J.D. In Press. Evaluation of a spawning habitat enhancement site for chinook salmon in a regulated California river., N. Amer. J. of Fisheries Management.

Merz, J.E., Setka, J.D., Pasternack, G.B., & Wheaton, J.M. In Press. Predicting fry production benefits from salmonid spawning habitat rehabilitation in a regulated California river, Canadian Journal of Fisheries and Aquatic Sciences.

Muotka, T., Paavola, R., Haapala, A., Novimkee, M., & Laasonen, P. 2002. Long-term recovery of stream habitat structure an benthic invertebrate communities from instream restoration, Biological Conservation, 105: 243-253.

Nehlsen, W., Williams, J.E., & Lichatowich, J.A. 1991. Pacific salmon at the crossroads: stocks at risk from California, Oregon, Idaho, and Washington., Fisheries, 16: 4-21.

Nijland, H.J., & Cals, M.J.R. (Eds) 2000. River Restoration in Europe: Practical Applications. Conference on River Restoration: Proceedings. Wageningen, The Netherlands.

NRC 1992. Restoration of aquatic ecosystems: science, technology, and public policy, Washington DC: National Academy Press.

Palmer, M.A., Ambrose, R.F., & Poff, N.L. 1997. Ecological theory and community restoration ecology, Restoration Ecology, 5(4): 291-300.

Pasternack, G.B., Wang, C.L., & Merz, J.E. 2004. Application of a 2D hydrodynamic model to design of reach-scale spawning gravel replenishment on the Mokelumne River, California, River Research & Applications, 20(2): 202-225.

Pretty, J.L., Harrison, S.S.C., Shepherd, D.J., Smith, C., Hildrew, A.G., & Hey, R.D. 2003. River rehabilitation and fish populations: assessing the benefit of instream structures, J Appl Ecology, 40(2): 251-265.

Tews, J., Brose, U., Grimm, V., Tielbörger, K., Wichmann, M. C., Schwager, M., & Jeltsch, F. 2004. Animal species diversity driven by habitat heterogenity/diversity: the importance of keystone structures, J of Biogeography, 31: 79-92.

Wheaton, J. M., Pasternack, G. B., & Merz, J. E. 2004a. Spawning Habitat Rehabilitation - II. Using Hypothesis Testing and Development in Design, Mokelumne River, California, U.S.A., International Journal of River Basin Management, 2(1).

Wheaton, J. M., Pasternack, G. B., & Merz, J. E. 2004b. Spawning Habitat Rehabilitation - I. Conceptual Approach and Methods, International Journal of River Basin Management, 2(1).