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Research

A Spatially Explicit Decision Support System for Watershed-Scale Management of Salmon

E. Ashley Steel [1], *Aimee Fullerton* [1], *Yuko Caras* [1], *Mindi B. Sheer* [1], *Patricia Olson* [2,3], *David Jensen* [1], *Jennifer Burke* [1,4], *Michael Maher* [1,5], and *Paul McElhany* [1]

ABSTRACT. Effective management for wide-ranging species must be conducted over vast spatial extents, such as whole watersheds and regions. Managers and decision makers must often consider results of multiple quantitative and qualitative models in developing these large-scale multispecies management strategies. We present a scenario-based decision support system to evaluate watershed-scale management plans for multiple species of Pacific salmon in the Lewis River watershed in southwestern Washington, USA. We identified six aquatic restoration management strategies either described in the literature or in common use for watershed recovery planning. For each of the six strategies, actions were identified and their effect on the landscape was estimated. In this way, we created six potential future landscapes, each estimating how the watershed might look under one of the management strategies. We controlled for cost across the six modeled strategies by creating simple economic estimates of the cost of each restoration or protection action and fixing the total allowable cost under each strategy. We then applied a suite of evaluation models to estimate watershed function and habitat condition and to predict biological response to those habitat conditions. The concurrent use of many types of models and our spatially explicit approach enables analysis of the trade-offs among various types of habitat improvements and also among improvements in different areas within the watershed. We report predictions of the quantity, quality, and distribution of aquatic habitat as well as predictions for multiple species of species-specific habitat capacity and survival rates that might result from each of the six management strategies. We use our results to develop four on-the-ground watershed management strategies given alternative social constraints and manager profiles. Our approach provides technical guidance in the study watershed by predicting future impacts of potential strategies, guidance on strategy selection in other watersheds where such detailed analyses have not been completed, and a framework for organizing information and modeled predictions to best manage wide-ranging species.

Key Words: *Chinook salmon; endangered species; habitat suitability; recovery planning; riparian; sediment routing.*

INTRODUCTION

Watershed-scale management of stream and river habitats is essential for coordinated efforts across multiple aquatic species; yet, developing an efficient and effective habitat management strategy over large spatial extents presents new challenges (Beechie et al. 2003, Roni 2004). Limitations in our understanding of how landscapes impact in-stream habitats and in how fish and other species respond to those habitats are magnified as we move from the reach to the watershed scale. Much of fisheries research, and in particular aquatic habitat restoration monitoring, is conducted at the reach scale and there are few tools available for appropriately scaling up results (Urban 2005). A further complication is that within a watershed, more than one threatened or endangered species is often the target of a particular management strategy. The ultimate goal of any salmon habitat management strategy is to improve future habitat conditions in such a way as to increase the likelihood of persistence of all species of concern. Although there may be large amounts of uncertainty in

[1]NW Fisheries Science Center, NOAA Fisheries, 2725 Montlake Blvd East, Seattle, Washington, USA 98112, [2]Pacific Watershed Institute, Olympia, Washington, USA 98504, [3]Washington State Department of Ecology, PO Box 47600, Olympia, Washington, USA 98504, [4]School of Ocean and Fisheries Science, University of Washington, Seattle, Washington, USA 98119, [5]Steward and Associates, 120 A, Suite d, Snohomish, Washington, USA 98290

predictions of future conditions, identifying how alternative watershed management strategies may impact future conditions across the watershed is a key to making the best habitat management decisions now. We present a scenario-based decision support system to evaluate watershed scale management plans for multiple species of Pacific salmon and we propose the fundamental structure of this decision support system as a model for managing migratory species over large spatial extents.

Pacific salmon are migratory species that spawn and often rear in freshwater. Salmonid populations in the Pacific Northwest have declined to a fraction of their historical abundance (Meengs and Lackey 2005). Recently, agencies such as the USDA Forest Service, private landowners, and local governments have begun to manage forests, streams, and rivers to protect and restore the habitat types necessary for all phases of salmonid life history. Although each species has unique habitat needs, there are many similar characteristics. Characteristic spawning habitats are low gradient, gravel-based channels and characteristic rearing habitats are smaller channels, as well as off-channel habitat, with some habitat complexity in the form of pools and overhanging banks; channel gradient preferences during rearing vary widely by species (Groot and Margolis 1991). During all life history stages, salmon require adequate cool and clean water. Large-scale processes, such as the delivery of sediment and water from the hillslopes to the channel, drive the development and maintenance of these habitats (Beechie and Bolton 1999). Therefore, effective management must also occur over these large scales.

In response to salmon population declines, a great deal of money has been and will likely continue to be spent on actions to restore and protect freshwater habitat for salmonids (NOAA 2004). During the years 2000 to 2003, the Pacific Coastal Salmon Recovery Fund and Pacific Northwest states allocated approximately U.S. $ 500 million to salmon recovery (NOAA 2004). Common habitat restoration and protection activities include road decommissioning and upgrades to reduce sediment inputs to headwater streams and reduce peak run-off from storm events; culvert or small dam replacements and modifications to improve fish passage and open currently inaccessible habitats; riparian plantings and harvest protections to provide shade, bank protection, and sources of large wood that can increase channel complexity; side channel reconstruction and dike removal to increase and improve floodplain habitats; and, placement of in-stream structures to increase habitat complexity, decrease stream power, and reduce transportation of sediment (Beechie and Bolton 1999, Beechie et al. 2003). Choosing the appropriate suite of actions and the most efficient locations for the actions is both difficult and essential. There is a vast literature on identifying restoration actions and locations within a watershed; yet, there is little research predicting the cumulative impact of multiple restoration actions within a watershed on local habitat conditions and on salmon population performance (Roni 2004).

We developed a spatially explicit decision support system for selecting and refining a watershed management strategy in the Lewis River watershed in southwest Washington, USA (www.nwfsc.noaa.gov/research/divisions/ec/wpg/documents/lrcs/LewisRiverCaseStudyFinalReport.pdf). Decision support systems have been applied to a wide range of problems (Finlay 1994, Turban 1995, Marakas 1999). Our decision support system enables a series of predictions about future landscapes given alternative watershed scale management strategies. It organizes empirical data and modeled predictions. Whereas some models were customized for application in the Lewis, the majority of the data and models existed prior to our analysis. These same models are currently used to make management decisions over large scales; however they are generally used in isolation and only to develop one best strategy. Our approach is novel in that we apply a suite of models, each of which predicts a different facet of habitat quality or quantity, and we apply the suite of models to multiple potential future landscapes. Our decision support system can guide the development of a watershed scale management strategy by linking and comparing many different models and by providing spatially explicit predictions of potential future conditions. The decision support system does not select a best strategy via an optimization procedure.

There are three essential and innovative features of our analysis that improve the usefulness of the results in making management decisions. First, we use both biological and habitat response models to evaluate future landscapes. Although biological response models predict the outcome of interest, in this example, salmon population performance, they necessarily rely on layers of assumptions. For most species and ecosystems, habitat response can be modeled with greater accuracy and precision; habitat outcomes provide a clear link to estimated population response. Second, we use multiple and often somewhat redundant response models. There are imprecisions and inaccuracies in predicting physical and biological outcomes over large spatial extents. Instead of relying on any one or two response models, our approach uses all available models. In this example, we apply eight evaluation models to the future landscapes. Each model builds on different input information and provides several outcome metrics of interest to decision makers. The use of multiple models and metrics enables decision makers to identify strategies that are robust to known uncertainties in input data and models. Third, our analysis is spatially explicit, allowing managers to view results in a map format and to see trade-offs between allocating funds to one part of the basin vs. another.

METHODS

Study site

The Lewis River watershed in southwestern Washington State, USA, encompasses 2760 km² and drains the western slope of the Cascade Mountain range, emptying into the Columbia River 140 km upstream of the mouth. There are three large, impassible dams on the North Fork of the Lewis River. Merwin Dam (RKM 31.4) was completed in 1931 and is currently a barrier to all anadromous fish (Fig. 1).

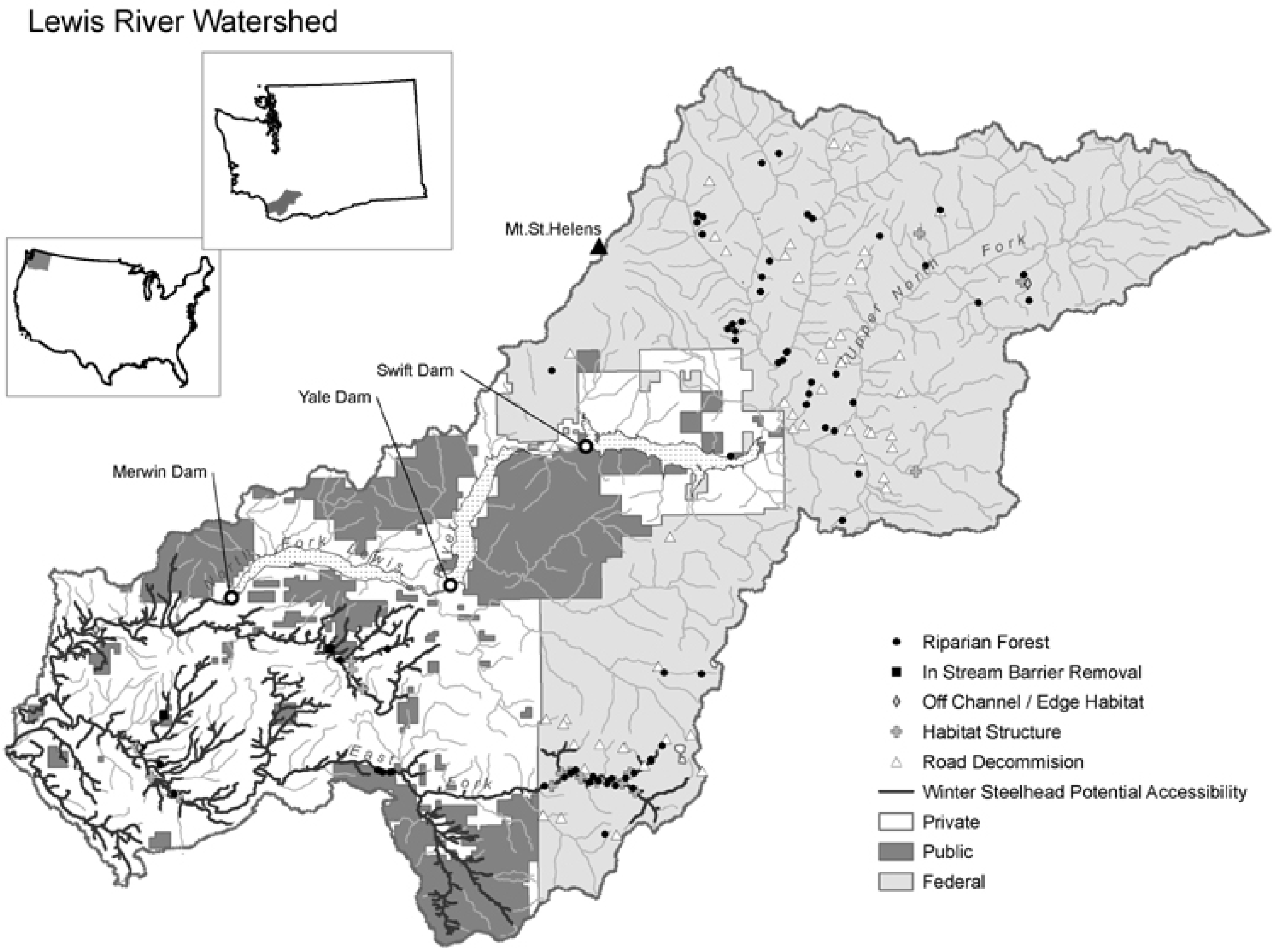
The landscape has historically been influenced by logging, fire, and volcanic activity. The majority of the headwaters of the basin are forested, and active logging was common until the 1980s. Currently, logging activities are greatly reduced, particularly on federal lands. All riparian areas are protected to some degree by the Washington Forest Practices Board (2004) and the U.S. Forest Service Northwest Forest Plan (USDA/USDI 1994). Stand replacement fires were common in the basin in the early part of the 20th century. Hydrology, sediment transport, and vegetation continue to show impacts from these historic fires, especially in the East Fork Lewis Watershed. The main tributaries on the north side of the Lewis basin drain the slopes of Mt. St. Helens, which erupted in 1980 (Fig. 1). Very fine sediments originating as volcanic ash from past eruptions characterize the northern subwatersheds of the upper Lewis drainage.

Small hobby farms, newer low-density residences, and agriculture dominate lowland areas. Gravel mining occurs in the lower parts of the East Fork of the Lewis River, and the mainstems of both the East and North Forks of the river are heavily channelized. Historically, the mainstem river was characterized by anastomosing channels on a wide, active floodplain that supported large deciduous trees (R2 Resources 2004). Using aerial photographs, we estimated that, historically, the East Fork Lewis River had 0.5 km of side channel for every kilometer of river. The human population in the watershed is relatively low, 14,157 people in 2002, and is concentrated in Woodland, Washington near the mouth of the river (U.S. Census Bureau 2000).

Four species of Pacific salmon inhabit the Lewis River watershed: Chinook (*Oncorhynchus tshawytscha*), steelhead (*O. mykiss*), coho (*O. kisutch),* and chum salmon (*O. keta*). These include eight populations of ESA-listed salmonids: North Fork Lewis coho, East Fork Lewis coho, Lewis River fall chum, North Fork Lewis spring Chinook, East Fork Lewis fall Chinook, Lewis early fall Chinook (brights), North Fork Lewis winter steelhead, and East Fork Lewis summer steelhead. Only a remnant population of spring Chinook remains in the basin. Historically spring Chinook spawned primarily in the upper watershed. Currently they spawn predominantly in the mainstem directly below Merwin Dam. Early fall Chinook populations are relatively abundant and spawn primarily in the mainstem sections of the East Fork Lewis River with some spawning in the mainstem North Fork Lewis River downstream of Merwin Dam. Steelhead populations are intermediate in abundance and spawn primarily in Cedar Creek, a tributary to the North Fork Lewis River below Merwin Dam (Fig. 1). Coho historically spawned throughout the basin and currently spawn in the main tributaries of the lower watershed. Chum historically inhabited mainstem habitats including what is now Lake Merwin, but did not use the upper basin. Currently, chum use habitat in the lower North Fork and East Fork Lewis Rivers (LCFRB 2004, NOAA 2005).

Current conditions in the Lewis River Watershed were estimated using GIS datalayers describing vegetation, road distribution, fish distribution, and land ownership (Table 1). To estimate conditions in 2003 not described in earlier GIS layers, restoration actions completed in the basin between 1998 and 2003, such as road decommissioning or barrier removals were identified and mapped (REO 2003,

Fig. 1. The Lewis River Watershed and its location in southwest Washington State, USA. The estimated linear extent of streams and rivers accessible to winter steelhead is identified with a thick line. Key disturbance elements include three large dams, and Mt. St. Helens, an active volcano. Landownership as private, public nonfederal, and federal are denoted with shading. Restoration actions completed between 1998 and 2003 and, therefore, included as part of the modeled current conditions are identified with symbols.



NOAA 2003, SRFB 2003, WDFW 2004; Fig. 1.) The landscape on which all watershed management strategies were modeled was created after incorporating the impacts of these real restoration actions. Because so many of the landscape evaluation models require stream width, we also developed a customized model of stream width from field measurements and attributed each reach with an estimated width (Steel et al. 2007; nwfsc.noaa.gov/research/divisions/ec/wpg/documents/lrcs/AppendixGBankfullWidthModel.pdf).

Table 1. GIS datalayers used in the decision support system (DSS). Most datalayers were modified slightly from their original source for this analysis. The source column includes an acronym for the agency providing the data and the year of the datalayer used in our analysis. Data processing notes are included in the description column. Full data references are included in the literature cited.

Data Source	Source	Description	Resolution
Sediment			
Soils on U.S. Forest Service land	USFS (1999)	U.S. Forest Service (Gifford Pinchot National Forest) forest soils and soil map units	1:15,840
Soils on state, county, and private lands	NRCS (2003–2004)	USDA Natural Resources Conservation Service Soil Survey Geographic Database (SSURGO) for Cowlitz, Clark, and Skamania Counties	1:250,000
Hydrology			
Stream hydrography (routed)	SSHIAP (2004)	Salmon and Steelhead Habitat Inventory and Assessment Program (SSHIAP) unpublished spatial data on hydrology and stream conditions (1:24,000) for Watershed Inventory Area (WRIA) 27	1:24,000
Stream hydrography (drainage enforced and routed)	Miller (2003)	Routed, cleaned and attributed stream hydrography generated to match SSHIAP hydrography following methods by Miller (2003); Generated to facilitate sediment routing and estimation of channel characteristics	1:24,000
6th Field Hydrologic Unit boundaries (HUCs)	BLM (2002)	Regional Ecosystem Office (REO) Hydrologic Unit Boundaries for Oregon, Washington, and California, Portland, Oregon, USA	1:24,000
7th Field Hydrologic Unit boundaries (HUCs)	Lewis County (2000)	Lewis County GIS (2001) data on 7th field hydrologic boundaries for the Lewis watershed	unknown
Topography and Geology			
Surficial geology	WDNR (2003)	Washington State Department of Natural Resources (WDNR) classification of geologic map units according to major lithology (WDNR 2003)	1:100,000
Slope stability	WDNR (2000)	WDNR predictive data layer of shallow-rapid slope stability from calibrated GIS-based models. Updated for the Lewis watershed using methods by Shaw and Vageois (1999)	1:24,000
Elevation	USGS (2003)	USGS 10 m drainage enforced Digital Elevation Model (DEM). Multiple DEMs mosaicked, and used to generate hydrographic stream layer, to associate streams with topographic features, and to generate lateral hillslope watersheds for stream segments	1:24,000
Hillslope	USGS (2003)	Hillslope gradient calculated for every 10-m gridcell in the mosaicked 10-m drainage enforced DEM, using ARC/INFO	1:24,000
Barriers			
SSHIAP barriers	WDFW (2004)	Salmon and Steelhead Habitat Inventory and Assessment Program (SSHIAP) unpublished data on fish passage barriers (1:24,000) for Watershed Inventory Area (WRIA) 27	1:24,000
Dams	BPA (2001)	Bonneville Power Administration (BPA) dams and possible hydroelectric development sites (BPA 2001); Original source database converted to a spatial datalayer	1:100,000

(con'd)

Political			
Regional ownership	ICBEMP (1995)	Interior Columbia Basin Ecosystem Management (ICBEMP) regional land ownership	1:100,000
Parcel ownership	Clark County (2004)	Land ownership, parcel boundaries, and land use for Clark County	1:24,000
Parcel ownership	WDNR (2005)	Land ownership, parcel boundaries, and land use statistics for Clark, Cowlitz, and Skamania Counties	1:24,000
County ownership	Comm-En Space	Washington Protected Lands Database (PLDB 2004, which includes spatial location and conservation status for private and public lands	-
Urban growth	Clark County (2004)	Urban growth boundary for Clark County	-
Land use	Clark County (2004)	Comprehensive plan and land use/zoning for Clark County	-
Vegetation			
Land and forest cover	IVMP (2001)	Interagency Vegetation Mapping Project, Western Cascades (Version 2.0) and Western Lowlands (Version 1.0) Spatial Data 1996 (BLM 2001)	30 m
National Land Cover Data	USGS (1999)	USGS classification of land cover data from LANDSAT TM satellite imagery (level 2). Generated by USGS using Anderson et al. (1976) protocols.	30 m
Fish Distribution			
Fish distribution	WDFW (2004)	Washington Department of Fish and Wildlife (WDFW) Salmon and Steelhead Habitat Inventory and Assessment Program (SSHIAP) data on fish distribution for Watershed Inventory Area (WRIA) 27	1:24,000
Transportation			
Roads	GP (1995)	Forest roads and associated attributes	1:24,000
Roads	WDNR (2005)	WDNR transportation data layer of roads, railroad, and other land and water transportation routes within Clark, Cowlitz, and Skamania Counties	1:24,000

Step 1: Identifying watershed management strategies

A watershed management strategy is a plan for spending money that specifies action types and action locations. The six modeled watershed management strategies were selected as examples of those that are commonly used or suggested for recovery planning. They included (1) spending all dollars on barrier removals, (2) spending half of available funds on barrier removals and half on riparian protection (e.g., Fig. 2A), (3) focusing all actions on federal lands, (4) using the Ecosystem Diagnosis and Treatment (EDT) model (Mobrand et al. 1997) reach prioritization output to prioritize actions, (5) landscape strategy, using GIS-based assessments of impaired riparian, sediment, and hydrologic function to select areas and action types using an expert panel to select a suite of actions and locations (Table 2, Fig. 3). The expert panel was selected to include managers from each agency with responsibility in the watershed as well as experts in watershed ecology who were less familiar with the particulars of the Lewis River. For each of these six strategies, we predicted what habitat conditions might look like 50 y in the future. Note that the GIS-based assessment strategy and the expert strategy each included multiple future landscapes that were modeled independently; results for these two strategies are presented as averages across all modeled landscapes. Also note that the EDT strategy is a plan for spending money according to an interpretation of the EDT model output (Appendix 1).

Each watershed management strategy spent a hypothetical budget of U.S. $ 2 million for habitat restoration and protection actions (Table 2). The hypothetical restoration budget of U.S. $ 2 million was based on the total dollars spent by the Washington State Salmon Recovery Funding Board during the years 2001–2003, per Water Resource Inventory Area (WRIA), multiplied by three to account for other sources of funding. Total dollars spent under each strategy (Table 2) were estimated using a series of economic models (Table 3). Our goal was to limit the dollars spent under each strategy to approximately the same value so that results could be compared across strategies. Because restoration actions require discrete fees, it was not possible for each strategy to cost exactly the same amount of money.

Step 2: Creating future landscapes

The second step in the analysis is to translate watershed management strategies into specific restoration and protection actions (Fig. 3). For each of the watershed management strategies, specific actions such as road decommissioning or riparian planting were identified and spatially located. The impacts of these actions were predicted using a series of simple relationships (Table 3), and a future landscape was created for each watershed management strategy. See Figs. 11–23 on pages 34-56 in http://www.nwfsc.noaa.gov/research/divisions/ec/wpg/documents/lrcs/LewisRiverCaseStudyFinalReport.pdf. The effect and cost of all actions were estimated using an instantaneous 50-yr time step. For example, the predicted benefits of riparian restoration included the amount of tree growth that we estimated would occur over 50 yr. These six watershed management strategies resulted in 13 potential future landscapes because the GIS-based assessment strategy and the expert strategy each included multiple future landscapes that were created independently (Table 4).

Step 3: Evaluating future landscapes

In the third step of our analysis, we quantify predicted future habitat quality and distribution and we predict the biological response to these habitat conditions. Eight landscape evaluation models were applied to each of 13 potential future landscapes. We define the term landscape evaluation model to include any set of rules used to estimate species-specific habitat conditions or biological response from landscape data. We generally selected pre-existing models and customized them for use in the Lewis River basin. Most models provided multiple evaluation metrics, e.g., number of km with reduced percent fine sediment and average reduction in percent fine sediment. The suite of landscape evaluation models is summarized below. Some models, e.g., the sediment routing model, provide both output metrics of interest to managers as well as input data for other models. For the most part, model output is only fed into a second model in the case of habitat models providing inputs for biological models. Further details about the development and application of these models are provided in Steel et al. (2007). Links between models are detailed in Figs. 2 and 3.

Hydrology model

The hydrology model estimates annual storm runoff (mm H_2O/yr) draining into each reach and 2.3-yr flood discharge (cm) for each reach. (1) The water erosion prediction procedure (WEPP) model was used to estimate the mean annual surface and shallow subsurface storm runoff in the watershed for each 30 × 30 m pixel (Lane et al. 1989, Flanagan and Livingston 1995). Variables used in the model were land cover, topographic slope, and soil texture. Application of the WEPP model to the Lewis River watershed was informed by extensive field verification (Steel et al. 2007). Field verification identified different effects of runoff on ash vs. non-ash soils. Riparian condition was used to modify surface and road sediment delivery to streams. On ash soils, fair or good riparian conditions reduced runoff volume by 38% and, on non-ash soils, they reduced runoff volume by 45%. (2) The 2.3-yr recurrence-interval flood discharge was estimated for each stream reach based on published relationships between gauge data, drainage area,

Fig. 2. Detailed description of the barriers and riparian watershed management strategy. Figure 2A describes subwatersheds targeted for riparian protection and barriers removed. Figures 2B–F describe the impact of those actions in terms of (B) scour improvement, (C) shade improvement, (D) reductions in fine sediment input, (E) potential Chinook survival changes and (F) changes in Chinook salmon capacity. Note that maps are summarized over different spatial extents as denoted in the legend for each map. The spatial allocation of funds for the barriers and riparian strategy is presented in Figure 3B.

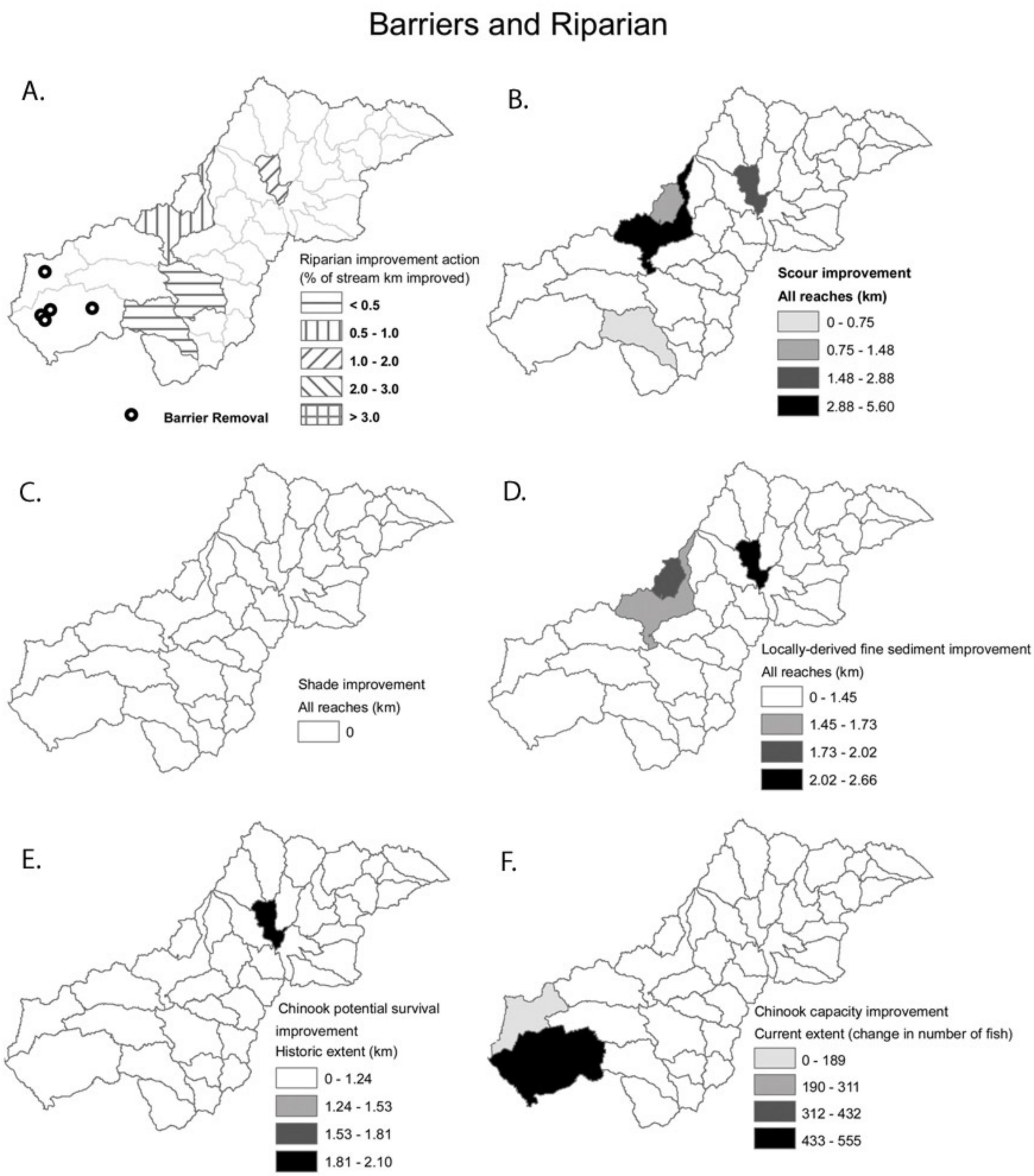


Fig. 3. Figures 3A–F describe the spatial allocation of funds for each of the six watershed management strategies. The size of the pie represents the total funds allocated/subwatershed. The slices of pie describe how funds were allocated among possible restoration and protection activities. A $U.S. 6000 pie is shown in the legend for scale. Proposed budgets for the landscape and expert strategies were averaged for display purposes.

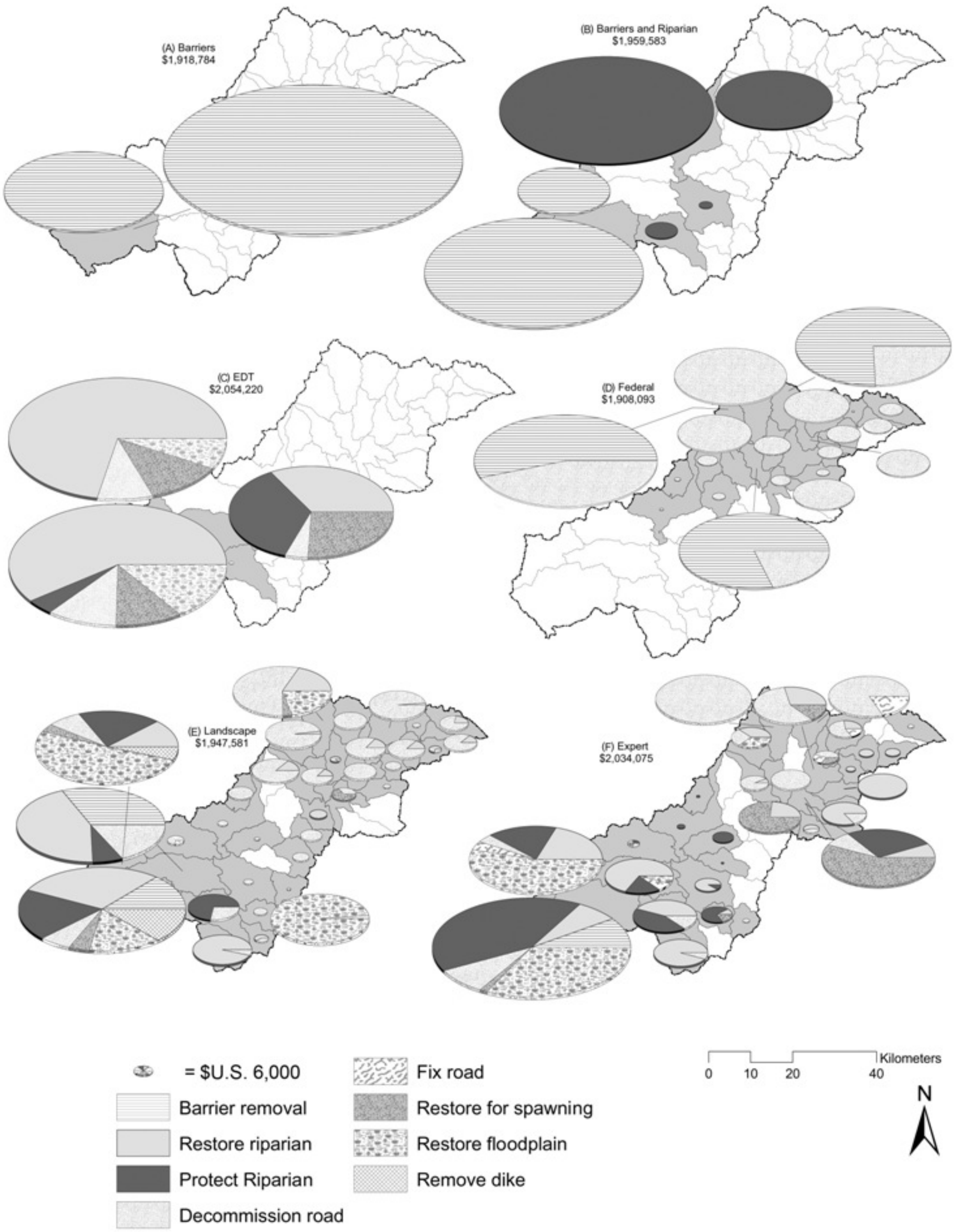


Table 2. Watershed management strategies. Note that barrier removal can describe either the physical removal of the barrier or modifying the barrier so that it is passable to fish.

Strategy name	Strategy description	Actions included in strategy	Area prioritization	Total cost
Barriers (Fig. 3A)	All funds allocated to barrier removal	Barrier removal	Barriers blocking the lowest cost/distance of historically accessible stream km are removed first.	$1,918,784
Barriers and Riparian (Fig. 3B)	50% of funds allocated to barrier removal and 50% of funds allocated to riparian protection	Barrier removal; riparian protection	Barriers blocking the lowest cost/distance of historically accessible stream km are removed first. Riparian protection was limited to public lands that did not already have a protection ordinance. Riparian areas were prioritized from upstream to downstream within those that were estimated to be in good condition (riparian condition model) and that bordered stream segments estimated to be of high spawning suitability (remotely-sensed suitability and capacity model).	$1,988,638
Federal (Fig. 3C)	50% of funds allocated to barrier removal and 50% of funds allocated to road decommissioning	Barrier removal; road decommissioning	Barriers on federal land blocking the lowest cost/distance of historically accessible stream km are removed first. Roads were selected by the amount of modeled sediment entering the stream segment to which that road segment drains (sediment model). Roads in areas of high sediment yield had the highest priority for decommissioning.	$1,908,093
EDT (Fig. 3D)	50% of funds allocated to reaches prioritized for protection and 50% of funds allocated to reaches prioritized for restoration.	Riparian protection; riparian restoration; in-stream restoration; floodplain restoration; and road decommissioning	A model was developed to convert EDT reach restoration and preservation priorities output to a set of specific restoration and preservation actions (Appendix A).	$2,015,401
Landscape (Fig. 3e)	Five pairs of local and modeling experts were given the results of the landscape scale riparian, sediment, and hydrology models (Table 4) and asked to develop a watershed management strategy based on model output and their own knowledge. They were asked to prioritize based on Chinook salmon.	Barrier removal; riparian protection; riparian restoration; in-stream restoration; floodplain restoration; and road decommissioning	Each pair of experts prioritized actions differently. All five strategies were modeled individually. The presented results are the average of these five modeling strategies.	$1,953,674
Expert (Fig. 3F)	Four teams of local experts were given all available information about the watershed, including information from other published watershed analyses (R2 resources 2004) and modeled output for current conditions from all available models. They were asked to prioritize based on Chinook salmon.	Barrier removal; riparian protection; riparian restoration; in-stream restoration; floodplain restoration; road decommissioning and fixing road	Each team of experts prioritized actions differently. All four strategies were modeled individually. The presented results are the average of these four modeling strategies.	$2,023,894

Table 3. Restoration action and economic models. Possible restoration and preservation actions are identified in the first column. The landscape impact column describes how the action was implemented on the landscape in our modeling framework. A description of how each modeled action was translated into EDT input data is found in the Appendix. The economic model column describes the cost estimated for each action type. C = Project cost in $U.S. (C); W = Channel width (m).

Restoration or preservation action	Economic model	Modeled landscape impact
Culvert removal	C = 178,430*ln(1.2W+0.61)-34,773 based on data from Evergreen Funding Consultants (2003)	Upstream reaches reclassified as passable, provided that they were historically accessible to fish
Riparian protection	Forest lands: cost of lost riparian timber production = $U.S. 10,000/acre. Nonforest lands: cost of acquisition (C/acre) depends on parcel size and current land-use designation: forested (40–80 acre plot) = $U.S. 7080; forested (>80/acre plot) = $U.S. 2856; open space = $U.S. 10,730; agriculture (min 20 acre plot) = $U.S. 6820; rural (< 5 acre plot) = $U.S. 16,997; rural (5–l10 acre plot) = $U.S. 14,456; rural (10–20 acre plot) = $U.S. 11,064; rural (min 20 acre plot) = $U.S. 7966; urban residential = $U.S. 40,344; urban commercial = $U.S. 39,199 Note: Riparian areas were protected to 60 m, however the costs were only calculated for the fraction of the riparian area not currently protected by county, state, or federal riparian ordinances.	Riparian functions and seral stage ↑ by one level when possible to improve, and riparian land cover was reclassified to 20-yr forested. This reduced the amount of sediment and hydrologic runoff entering the reach.
Riparian planting	Riparian planting only occurred on areas in which costs were not prohibitive. These included reaches for which > = 35% of the area within 20 m of the channel was < 5% hillslope and > = 50% of the area within 20 m of the channel was not in bare ground, shrubs, or short grass. The cost for riparian planting was estimated as C/acre = $U.S. 15,000 (slope < 0.05).	Riparian functions and seral stage ↑ to the best possible level, and riparian land cover was re-classified to 20-yr forested. This reduced the amount of sediment and hydrologic runoff entering the reach.
In-stream restoration	C/km = $78,593	Improved spawner capacity in reach by adjusting input variables. Small streams (BFW ≤ 25 m): redds/km ↑ to 90th percentile of estimated current values Large streams (BFW > 25 m): spawnable area ↑ by 32%
Floodplain restoration	C/ stream km = $U.S. 155,507	Increased length of reach by 39.4% to represent inclusion of historical side channels, as determined from aerial photographs. Habitat conditions were inherited from existing reach, and may have been modified by other actions. An outline of the floodplain for the Lewis River watershed (WDFW 2003) was used to identify segments appropriate for side channel restoration unless specifically identified in the landscape and expert strategies. All mainstem North Fork, East Fork, and Upper North Fork segments within the floodplain boundaries were considered, as well as tributaries that were within the extent of the floodplain.
Road decommissioning	C/road km = $U.S. 12,427	Reduced length of existing roads by 95% in areas draining to reach; thereby reducing sediment input
Road repair	C/road km = $U.S. 6214	Reduced length of existing roads by 50% in areas draining to reach; thereby reducing sediment input

Table 4. GIS-based models to evaluate the current landscape and to generate the landscape-watershed management strategy. change (Δ).

Model	Model description	*Output metrics*
GIS-based sediment	GIS-based assessment of relative differences in estimated historical and current sediment budgets. Forested area budgets based on roads, mass wasting, area in clearcuts, hillslopes, and erosion rate studies, and USFS modified WEPP (Elliot et al. 1995). Agricultural area budgets based on the modified universal soil loss equation (RUSLE) using soil erosivity, slope, and land use and land cover (Beechie et al. 2004, Flanigan and Livingstone 1995).	6th field HU summaries of annual yield (kg/yr); % Δ between estimated historical and current conditions
GIS-based hydrology	GIS-based assessment of relative differences in estimated historical and current runoff estimated from land cover, land slope, and soil texture using the modified WEPP in forested areas (Elliot et al. 1995) and WEPP in agricultural areas; and coarser-scale impact ratings based on forested areas: % immature vegetation and road density; lowland areas: % impervious areas (Beamer et al. 2000, Booth and Jackson 1997, Dinicola 1989, Lunetta et al. 1997).	6th field HU summaries of % impaired due to impervious areas; % Δ between estimated historical and current conditions

bankfull width and depth, and land use and cover (Dunne and Leopold 1978, Black 1991, Moscrip and Montgomery 1997). The 2.3-yr flood was used as an indicator of the mean annual flood and channel forming flow. Flood frequency and sediment transport analysis in the Lewis watershed indicated that the 2.3-yr flood is a good estimate of the magnitude of flood that initiates bedload transport (PWI 1998, PacificCorp 2002). More details can be found in nwfsc.noaa.gov/research/divisions/ec/wpg/documents/lrcs/AppendixESurfaceSedimentErosionandRunoff.pdf.

Sediment model

The sediment yield model predicts annual yield (kg/yr) of surface, road, and mass wasting sediment delivered to each stream reach. (1) Surface sediment yield was generated through a modified Water Erosion Prediction Procedure (WEPP) model for each 30 x 30 m pixel in the watershed. Variables used in the WEPP model were land cover, topography (slope) and soil texture (Lane et al. 1989, Flanagan and Livingston 1995); (2) Field data on road sediment yield (PWI 1998, Pacific Corps 2002) was supplemented with data generated through two U.S. Forest Service models, WEPPROAD and XDRAIN (Elliot et al. 1995, Elliot and Hall 1997). Road sediment yields were estimated for all road surfaces and prisms based on underlying soil, road slope, riparian condition, and distance from streams. Field verification also identified different sediment rates on ash vs. non-ash soils. Riparian condition was used to modify surface and road sediment delivery to streams. On ash soils, fair or good riparian conditions reduced sediment inputs to the stream by 38% and, on non-ash soils, they reduced sediment inputs by 45%. (3) Mass wasting sediment yield was predicted from modified published GIS-based slope stability models (Montgomery and Dietrich 1994, Shaw and Vaugeois 1999). The modifier variables included soil characteristics, road density, and land cover in adjacent hillslopes. More details can be found online at: nwfsc.noaa.gov/research/divisions/ec/wpg/documents/lrcs/AppendixESurfaceSedimentErosionandRunoff.pdf.

Sediment and hydrology routing

Lateral sediment and runoff delivered to each reach were cumulatively routed through all downstream reaches using the 2.3-yr flood as the channel forming flow. The customized routing model provided information on source of sediment and stream response to sediment inputs. Gross morphologic indicators of drainage area, channel gradient, and valley width were used to delineate broad channel types and identify potential zones of transport and deposition (e.g., Montgomery and

Buffington 1997). The routine uses a series of variables to estimate the deposition of sediment including contributing area per segment, flood discharge modifications, empirical models for bed textures and fines, estimates of sediment yield per stream reach (kg/y) and bed scour. Channel sediment size field data (*unpublished data* from US Forest Service, PWI 1998) and size classes of incoming sediment estimated from the SSURGO database (NRCS 2004) and landslide surveys (*unpublished data*, Earth Systems Institute) were used to predict the amount of fine sediment deposited, and an index of bed scour for unmodified and current conditions for each reach. The reservoirs were treated as sediment and flow sinks; sediment and 2.3-yr flood estimates were reset to base levels for stream reaches immediately downstream of the dams. Details are available in Steel et al. (2007), Appendix F. Available online at: nwfsc.noaa.gov/research/divisions/ec/wpg/documents/lrcs/AppendixFSedimentRouting.pdf. Output metrics from the routing model include reach-specific estimates of fine and coarse sediment, by source, entering laterally and from upstream; % fine sediment deposited; and an index of bed scour.

Riparian condition model

Three riparian functions are estimated from remotely sensed vegetation data using a logical model nwfsc.noaa.gov/research/divisions/ec/wpg/documents/lrcs/AppendixHRiparianFunctionModel.pdf. The riparian model combines bankfull width, elevation from a digital elevation model (DEM), channel gradient, and estimates of riparian vegetation cover, i.e., total cover, percent coniferous or deciduous, and tree size (dbh) to predict qualitative riparian conditions within 60 m of each bank (FEMAT 1993, Lunetta et al. 1997, WFPB Assessment Method Riparian Module 1997, BLM 2001, Montgomery et al. 2003). Shade and large woody debris models were modified from the WFPB (1997) method, and the pool-forming conifer model was based on Beechie et al. (2000), Buffington et al. (2002), and Montgomery et al. (2003). Model outputs include assessments (good/fair/poor) for shade function, potential large woody debris recruitment, and potential recruitment of pool-forming conifers. Our large-woody debris recruitment model was customized for our application to incorporate deciduous trees, which historically dominated the landscape in the Lewis River basin.

FishEye

FishEye is a logical model that combines habitat preferences, e.g., channel gradient, bankfull width, sediment deposition, bed scour, and hydrologic regime, by species based on published fish-habitat relationships (e.g., Salo 1991, WDNR 1991, Montgomery et al. 1999, WDFW 2000, WFPB 2000, Burnett 2003). It is available online at: nwfsc.noaa.gov/research/divisions/ec/wpg/documents/lrcs/AppendixJFishEye.pdf). FishEye output metrics include species-specific natural habitat suitability ratings for only the factors that are generally not modified by human actions, e.g., gradient, stream width, and hydrologic zone, and species-specific observed habitat suitability ratings for both current and future conditions that also include habitat factors impacted by management, e.g., riparian, sediment, and bed scour. Predicted suitability ratings identify areas that have both high natural suitability and low anthropogenic influence.

Remotely sensed suitability and capacity model

This is a logical model that uses a combination of bankfull width, stream gradient, and seral stage of riparian area to classify all stream reaches as good, fair, or poor Chinook salmon spawning habitat (Bartz et al. 2006, Beechie et al. 2006). (nwfsc.noaa.gov/research/divisions/ec/wpg/documents/lrcs/AppendixIChinookSpawnerSuitabilityandPotentialCapacityEstimates.pdf). The model was built from empirical data on spawner distributions (Lunetta et al. 1997, Beamer et al. 2000). Empirical estimates of spawner densities in good, fair, and poor habitat enable estimates of total spawner capacity in a watershed. The model has been used for multiple nearby watersheds (Beechie et al. 2006) and was only slightly modified for use in the Lewis. Our modification was to allow older deciduous forests to be classified as old riparian habitat. Model output metrics include habitat suitability ratings (good/fair/poor) and spawner capacity estimates for Chinook salmon.

Ecosystem Diagnosis and Treatment

The Ecosystem Diagnosis and Treatment model (EDT) is a proprietary habitat suitability model that is often used in isolation in most watershed-scale habitat recovery-planning projects in the region. (Mobrand Biometrics, Inc. 2004). Model output metrics used to evaluate future landscapes include watershed-scale productivity, capacity, and equilibrium abundance estimates for Chinook salmon. Note that the EDT model was used both to generate a watershed management strategy (above) and to estimate future biological response for all six strategies.

Sediment and survival model

Statistical relationships between the amount of fine sediment deposited in a reach and the likelihood of survival were developed based on a compilation of published studies, agency reports, and theses (N=14). Published studies included Tappel and Bjornn (1983), Hall (1986), Reiser and White (1988), Bennett et al. (2003) for Chinook salmon, Hall and Lantz (1969), Cederholm and Lestelle (1974), Cederholm and Salo (1979), Tappel and Bjornn (1983) for steelhead, Tagart (1984), Hall (1986), and Reiser and White (1988) for coho salmon. The sediment survival model is a pair of logistic regression equations: a combined equation for steelhead and Chinook and an equation for coho salmon. The equations predict egg-to-fry survival as a function of the percent fine sediment in the channel. Details of the sediment survival model are available in Steel et al.(2007), Appendix K (www.nwfsc.noaa.gov/research/divisions/ec/wpg/documents/lrcs/AppendixKFunctionalRelationships.pdf). Model output metrics include egg-to-fry survival estimates and confidence intervals around that survival estimate for Chinook, steelhead, and coho salmon.

Step 4: Comparing the future landscapes

In the fourth step, we synthesize modeled predictions of both future physical habitat conditions and potential biological response to those conditions that would result from each of the six watershed management strategies (Table 5). We summarized results for individual reaches into a series of watershed-scale evaluation metrics. For sediment, hydrology, and riparian results, we summarized metrics over all reaches in the watershed. For habitat suitability, spawner capacity, and egg-to-fry survival, we summarized metrics over reaches currently accessible to winter steelhead, the most far-ranging species. Metrics fall into several general categories: (1) km improved, (2) km newly accessible, and (3) EDT outputs. We calculated km improved as the length (km) of all reaches in a spatial extent, i.e., entire watershed, or fish-accessible, where conditions improved because of the effect of a restoration action. Habitat suitability improvements included increases in both quantity and quality of habitat. Newly accessible habitat was summarized for each species as km opened by barrier improvements or floodplain restoration. For strategies with more than one modeled future landscape, outcome metrics were averaged. Although the potential for salmon reintroduction above the dams was not modeled explicitly, we quantified potential future habitat conditions over the area that would become accessible to salmon under such a scenario to provide estimates of potential habitat in those areas, e.g., sediment inputs. Limitations on available data prevented us from applying EDT to areas above the dams.

RESULTS

Each watershed management strategy resulted in a unique distribution of habitat changes (Table 5, Fig. 3) that could be traced to the spatial distribution of actions. Improvements predicted from U.S. $ 2 million in restoration and protection actions were a very small fraction of the potential improvement in any habitat metric (Table 5). Because changes in sediment and hydrology were routed downstream, habitat changes could also be detected in downstream subwatersheds (e.g., Figs. 2D and 2E). These habitat changes were captured in a suite of habitat outcome metrics (Table 5). Biological response to these habitat changes was predicted using the biological response models described above and captured in a suite of biological outcome metrics (Table 5). Increases or improvements in suitable habitat was relatively constant across species except for chum salmon (Table 5).

No watershed management strategy performed best with respect to all of the habitat or biological response metrics (Table 5, Figs. 4 and 5). The strategy emphasizing actions in the upper watershed, the federal strategy, performed best with respect to reductions in flood discharge (Fig. 4D) and some types of sediment input (Figs. 4C and 5B). However, the federal strategy ignored downstream habitats that may have higher potential suitability and that are currently accessible to fish (Fig. 3D, 4E, 4F, 4G). The Ecosystem Diagnosis and Treatment strategy (EDT), which spent the most

Table 5. Results for selected metrics used to evaluate future impacts of each of the six watershed management strategies. Evaluation metrics are summarized over all reaches in the watershed for sediment, hydrology, and riparian metrics, and over reaches currently accessible to winter steelhead for habitat suitability, spawner capacity, and egg-to-fry survival. Newly accessible habitat is summarized for each species. The maximum potential column describes the difference between estimates for current and historical conditions, an estimate of the maximum improvement in habitat condition or biological response that could be expected with infinite resources. Habitat suitability improvements include increases in both quantity and quality of habitat. Barriers and Riparian management strategy (Bar./Rip.), mass wasting (MW), pool-forming conifers (PFC), large woody debris (LWD), 90% confidence interval (CI); change (Δ), an increase in the value over current conditions (↑), a decrease in the value (↓). Fine sediment = 0.25 to 1.0 mm. [1]Laterally derived sediment is sediment entering a reach from adjacent hillslopes.
[2]Locally derived sediment = sediment entering a reach from adjacent hillslopes and from upstream reaches.

Evaluation Metric	Barriers	Bar./Rip.	EDT	Federal	Landscape	Expert	Max Potential
Sediment							
km laterally derived[1] surface sediment ↓	0.0	4.7	27.7	0.0	11.6	11.5	5569
km locally derived[2] surface sediment ↓	0.0	14.6	58.2	0.0	56.1	56.7	5805
km laterally derived[1] MW sediment ↓	0.0	0.8	0.0	9.3	3.0	2.2	2261
km locally derived[2] MW sediment ↓	0.0	5.8	7.6	90.3	42.0	29.5	3412
km laterally derived[1] road sediment ↓	0.0	0.0	70.3	256.9	142.6	98.9	4247
km locally derived[2] road sediment ↓	0.0	0.0	105.9	716.7	457.8	239.5	5224
km % of fine sediment entering reach ↓	0.0	7.0	108.0	710.5	442.9	229.6	4230
km % fine sediment deposited in reach ↓	0.0	5.9	101.7	705.2	424.8	215.2	5065
km fines deposited is newly <10%	0.0	0.0	4.7	24.8	9.8	7.8	724
Hydrology							
km hydrologic runoff entering reach ↓	0.0	4.7	29.0	0.0	11.7	11.9	5596
km 2.33-yr flood discharge ↓	0.0	5.0	6.2	352.2	199.1	105.2	5466
km the index of bed scour ↓	0.0	8.6	97.4	750.5	470.2	231.3	5325
Riparian							
km shade score has ↑	0.0	0.0	19.3	0.0	7.3	8.5	1719
km PFC score has ↑	0.0	0.0	5.5	0.0	8.3	5.4	818
km LWD score has ↑	0.0	0.0	27.2	0.0	9.6	10.3	3819
km all 3 riparian scores ↑	0.0	0.0	27.2	0.0	9.1	10.7	3953
Habitat suitability							
km suitability ↑ for chum	10.7	5.2	17.3	0	2.4	3.7	247
kmsuitability ↑ for spring Chinook	38	22.3	12.5	0	5.6	3.9	1020

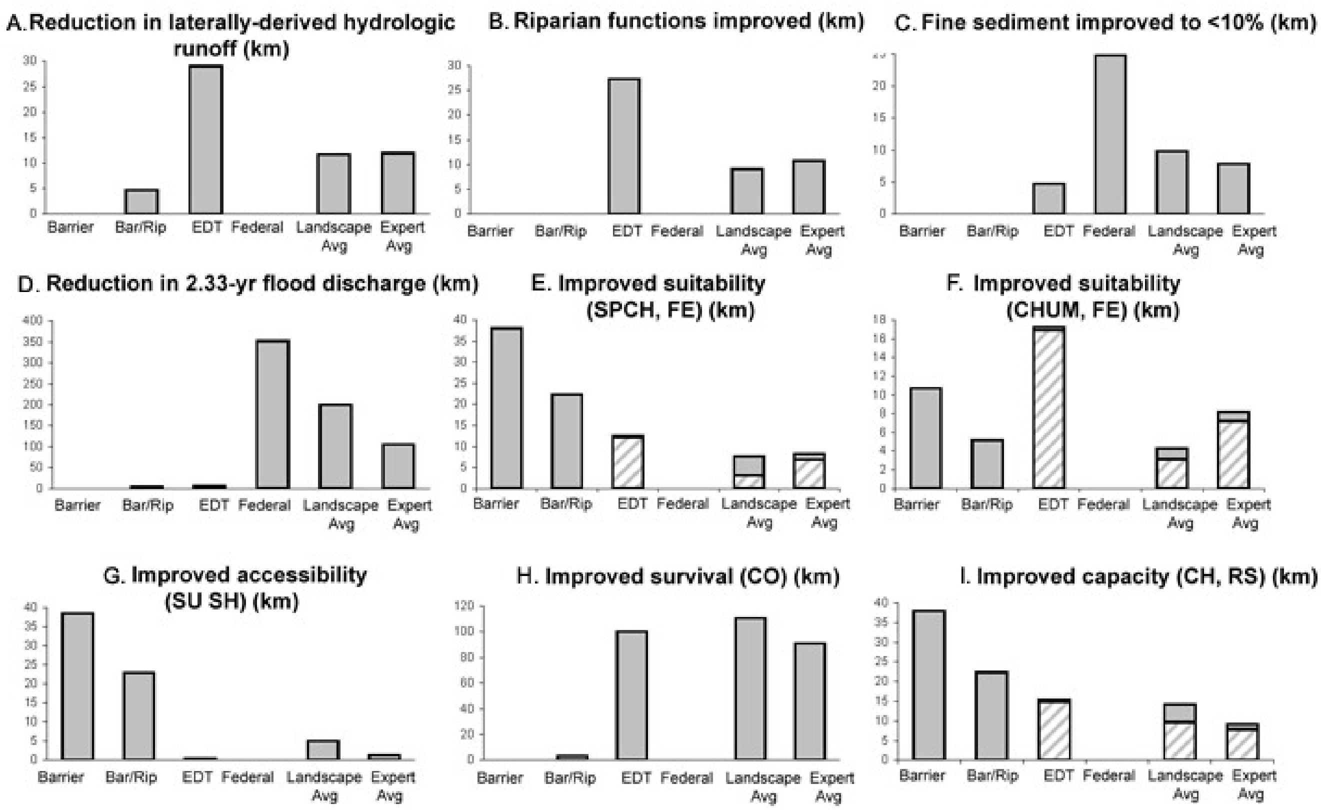
(con'd)

km suitability ↑ for fall Chinook	38	22.3	19.2	0	5.7	3.8	1000
km suitability ↑ for winter steelhead	38.5	22.8	12.5	0	5.7	3.9	1123
km suitability ↑ for summer steelhead	38.5	22.8	12.5	0	5.6	3.9	1090
Spawner Capacity (Chinook)							
km capacity ↑ (due to Δ in reach quality)	0.0	0.0	14.8	0.0	9.2	5.3	168
km capacity ↑ (above and Δ in accessibility)	38.0	22.3	15.2	0.0	13.7	6.6	679
Egg-to-dry survival							
km Chinook/steelhead survival ↑	0.0	0.0	96.6	0.0	73.0	58.0	1015
km coho survival ↑	0.0	0.0	96.5	0.0	70.6	56.1	1014
EDT outputs (current w/out harvest; fall Chinook)							
Capacity	24370	24370	25102	24370	24402	24489	29897
Equilibrium abundance	22367	22367	23305	22367	22406	22523	28265
Productivity	26.89	26.89	30.83	26.89	26.99	27.62	40.02
Accessibility							
km newly accessible to chum	10.7	5.2	0.4	0.0	1.2	1.0	66
km newly accessible to coho	38.0	22.3	0.4	0.0	4.5	1.3	514
km newly accessible to spring and fall Chinook	38.0	22.3	0.4	0.0	4.5	1.3	531
km newly accessible to winter and summer steelhead	38.5	22.8	0.4	0.0	5.0	1.3	588

money on riparian restoration and protection, performed best with respect to some riparian functions, shade and large-woody debris recruitment, (Figs. 4B and 5A) and provided the most dramatic reductions in lateral hydrologic flow volumes because of improved riparian areas which reduced lateral runoff (Fig. 4A). This strategy focused almost completely on mainstem reaches in the lower watershed and the resulting future landscapes showed little improvement with respect to increases in accessible habitat or reductions in sediment delivery in the upper watershed. The EDT strategy also showed significant reductions in surface-derived sediment (Fig. 5B) and strong improvements in habitat suitability for chum (Fig. 4F) because of the improvements in riparian condition in the lower watershed. The barriers strategy, which opened up only nine barriers, performed extremely well with respect to improvements in suitability, accessibility, and capacity for multiple species (Figs. 4E,4F,4G,4I). This strong performance was a result of newly accessible habitat in two lower subwatersheds; however, the rest of the Lewis River watershed and large-scale habitat processes such as sediment delivery, hydrologic function, and riparian condition were unchanged. The barriers and riparian strategy balanced the strengths of opening up some new habitat in the lower watershed with riparian improvements throughout the watershed. The landscape and expert strategies, which averaged several future landscapes, had the widest spectrum of restoration and preservation actions (Figs. 3E and 3F). These strategies tended to balance performance on habitat and biological metrics and rarely had the best or worst performance on any one metric (Figs. 4 and 5).

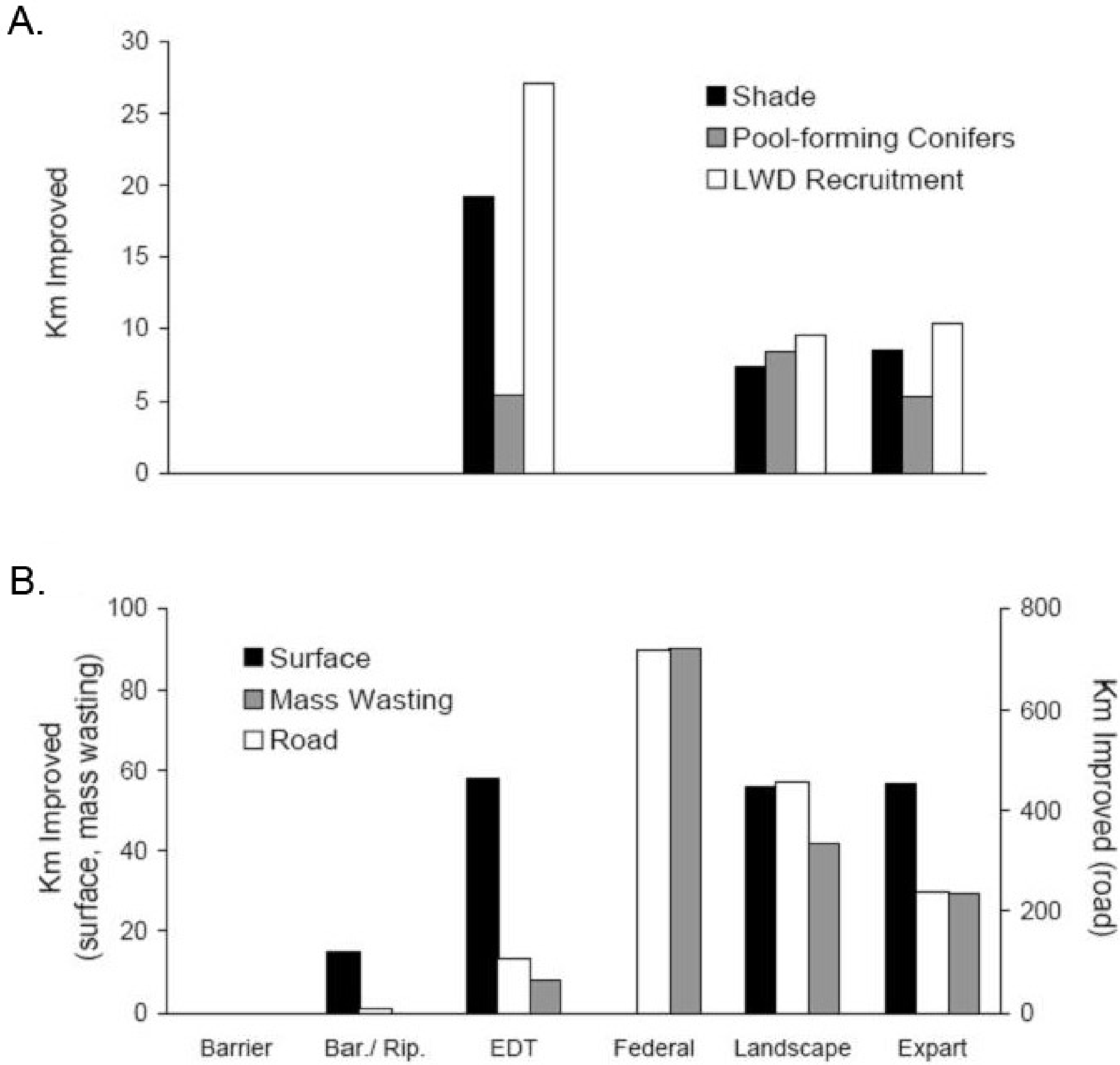
The largest gains, across all six watershed management strategies, for sediment included 56–58 km of stream with a reduction in locally derived

Fig. 4. Habitat and biological responses to the six watershed management strategies. Panels A–D are summarized over all reaches. Panels E–I are summarized over all reaches accessible to winter steelhead in the future landscape being evaluated. Predicted responses to the landscape and expert strategies are presented as the average over all modeled landscapes. In panels E, F, and I, the solid bars describe increases in suitability or capacity that result from increased accessibility and the hatched bars represent increases in suitability or capacity that result from improvements in the quality of habitat that was accessible under current conditions. Note that the y-axis-scale changes between metrics. spring Chinook salmon (SPCH); summer steelhead (SUSH), coho salmon (CO), Chinook salmon (CH), FishEye model (FE), remotely sensed capacity model (RS).



surface sediments (EDT, landscape, and expert strategies), 90 km of stream with reduced sediment inputs from mass wasting (federal strategy), and 717 km of stream with reduced road-derived sediment (federal strategy). The largest length of stream with a reduction in flood magnitude was 352 km (federal strategy). The longest gain in riparian conditions was about 27 km of newly improved habitat (EDT strategy). Maximum km of new or improved habitat suitability, as estimated using FishEye, was about 38 km for all species (barriers strategy) except chum, which had a slightly larger increase in suitability (17 km) with the EDT strategy. The maximum length of stream with an increase in spawner capacity estimates was 38 km (barriers strategy). The maximum length of stream improved with respect to egg-to-fry survival was 97 km for steelhead, Chinook, and coho salmon. The maximum increase in accessible stream distance within the historical species range was only 10.7 km for chum salmon but approximately 38 km for the other modeled species (barriers strategy). The

Fig. 5. Detailed descriptions of predicted changes in (A) riparian function and (B) fine sediment inputs across the six watershed management strategies. Predicted responses to the landscape and expert strategies are presented as the average over all modeled landscapes. Note that the y-axis scale changes between metrics; there are two y-axes in panel B.



maximum fall Chinook salmon capacity predicted by EDT was 25,102 fish (EDT strategy) for the basin; however, this was within 700 fish of the minimum fall Chinook capacity across all six watershed management strategies (Table 5). Because of the number and, in some cases, complexity of the models used in this analysis, confidence intervals for these estimates are not yet available.

The largest gains in riparian function were achieved using the EDT strategy (Table 5, Figs. 4B and 5A). These gains were not consistent across all three riparian functions. The EDT strategy outperformed the other strategies with respect to large-woody debris recruitment and shade function but the differences in recruitment of pool-forming conifers was less dramatic between strategies (Fig. 5A). Likewise, the federal strategy did much better at reducing road sediment and mass wasting sediment but, because all riparian areas on federal lands are already protected, no riparian restoration or protection actions were added and the federal strategy showed no improvement in surface-derived sediment. The EDT strategy, emphasizing riparian protection and restoration, showed the largest lengths of stream with improved surface-derived sediment (Fig. 5B) but these were quite similar to improvements observed with the landscape and expert strategies.

DISCUSSION

Our decision support framework organizes predictions for identifying the best watershed management strategy. No single strategy will maximize all possible outcomes. But, by examining multiple habitat and biological metrics, the best strategy or combination of strategies for meeting a particular set of goals can be selected. By including models that explicitly represent watershed processes, such as routing of sediment and water, we provide managers with tools for examining the more certain habitat impacts at the same time as the less certain biological response predictions. Each model has inherent inaccuracies, imprecisions, and biases. Because of these model limitations, experts, modelers, and decision makers have demanded a reduced reliance on individual models (Burgman et al. 2005). By using output from multiple models, we provide more robust predictions on which to make decisions. The final strategy selection will require subjective decision making based on local habitat knowledge, current population status of all affected species, insights about local model accuracy, social values, and risk tolerances.

Although our economic algorithms are crude, these analyses also provide a rough estimate of the expected physical and biological outcomes given optimistic yet realistic watershed management budgets. In the Lewis River, U.S. $ 2 million was not sufficient to solve all of the problems. Only a very small fraction of the maximum potential improvements in habitat condition or biological condition were achievable for any model evaluation metric (Table 5). The allocation of available funds is therefore essential, as it will determine future watershed conditions. By carefully structuring the available information and estimates, as in a decision support system, managers can maximize the impacts of available restoration funds. Sensitivity analyses exploring the impacts of economic assumptions on the selection of a best strategy are underway to remove any potential biases of our crude economic models.

The structure of our decision support system improves on existing alternatives because it is robust to uncertainties in any one particular model. In other words, even if one model is inaccurate or imprecise, the overall assessment of each watershed management strategy is unlikely to be strongly impacted. The most common on-the-ground approach for developing a watershed management strategy is to use a single model or approach. In the Pacific Northwest, the Ecosystem Diagnosis and Treatment strategy (EDT), model is often used as the sole decision making tool. We demonstrate here that this model can be incorporated into a more robust decision-making scheme that includes alternatives such as expert panels or GIS-based landscape analyses. Population viability analyses are also commonly used (e.g., Ellner and Fieberg 2003) to evaluate population status but this approach does not explicitly link population performance with habitat conditions and therefore cannot be used to develop a habitat restoration plan. In other regions, decision support systems have been used with success (e.g., Reynolds and Hessburg 2005) to integrate landscape evaluation and restoration planning. Decision support frameworks such as the Ecosystem Management Decision Support (EMDS) have been used in other salmon recovery planning efforts (USFS 2005); yet, they have not incorporated economic considerations or relied as strongly on multiple models. The use of alternative future landscapes, as was done for the Willamette River Initiative (Baker et al. 2004), provided our approach with a clear framework for evaluating how current management actions might impact future landscape pattern.

Technical guidance for the Lewis River watershed

Using these multiple metrics, models, and future scenarios to identify a habitat strategy for the Lewis River basin will require a subjective assessments of the major issues facing the basin, species priorities, the value of each metric, and the perceived accuracy and precision of the models. To demonstrate how this decision support system might be used to identify an on-the-ground watershed management strategy, we provide four alternatives based on fictitious restoration beliefs and values. The real selection of an on-the-ground strategy will depend on real restoration values, ongoing management of non-habitat impacts on salmonids such as harvest and hatcheries and, of course, social and political constraints beyond the scope of our analysis.

In our first example, we imagine a manager, Manager A, interested predominantly in steelhead. He strongly believes that juvenile capacity is limiting steelhead production, particularly in the lower reaches of the river. Although the data do not exist to make an empirical life-cycle model, 20 yr of working in the Lewis River and extrapolation from other watersheds have provided an excellent basis for this belief. Manager A is also interested in coho salmon, which have recently been listed as threatened. He believes that fall Chinook populations are strong enough to warrant little concern and spring Chinook salmon will be so greatly improved with passage above the three large dams that further focus is unnecessary. Because he believes that steelhead juvenile capacity is limiting, Manager A will spend 50% of available funds using the barriers strategy. Barriers selected for improved passage would be identical to those selected with the barriers/riparian strategy as 50% of funds were spent on barrier removals in that strategy. Barriers removed or improved tended to be in the lower portions of the river (Fig. 2) where Manager A believes the greatest improvements in steelhead and coho salmon population dynamics are possible. This strategy not only opened up the most habitat overall but provided the greatest increase in suitable habitat, as estimated using the FishEye model, for all species except chum salmon. However, this strategy does little to improve existing habitat. The other 50% of the funds would therefore be spent using the EDT strategy. The EDT strategy provided the greatest improvements in key riparian functions which will translate into decreases in water temperature, through increased shade, and increases in habitat complexity, because of increases in potential wood inputs. The EDT expenditures on riparian condition in the lower watershed also translated to the highest improvements in egg-to-fry survival for steelhead, Chinook, and coho by reducing lateral sediment inputs in the lower basin.

Manager B is concerned about the extinction risk faced by spring Chinook. She feels that the costs associated with providing spring Chinook access above and between Merwin, Yale, and Swift reservoirs will be wasted without significant habitat improvements in the upper basin. She has not had positive experience with follow-through from private landowners in other basins and she is impressed by the large lengths of stream that could be improved with respect to sediment and hydrologic processes using the federal strategy. She chooses to dedicate 80% of available funds to the federal strategy, which includes road decommissioning and barrier removals on federal lands, and the remaining 20% to riparian protection on non-Federal lands in the upper watersheds. To assess the combined impact of this allocation of funds, she might rerun the decision support system with this new watershed management strategy.

Manager C might be a committee tasked with generating a consensus watershed management strategy. They are interested in building on the expertise of local managers and modelers and would like to balance improvements in watershed processes with increases in habitat quality and quantity in the lower watershed. There are conflicts among members of the group that reduce confidence in any one particular model and the group is interested in improving the status of multiple species. Some members note that the simpler strategies such as barriers, barriers/riparian, and federal exclude several types of restoration actions such as dike removal and floodplain restoration, athough expensive, have been very successful in other basins. They choose to spend all of their restoration dollars using the expert strategy and also to adopt an adaptive management approach by revisiting the decision support system every two years and continuing to customize and refine the models with empirical monitoring data.

Manager D has few choices. For political reasons, she expects to be forced into a fairly opportunistic watershed management approach. She benefits from the decision support system output by observing that actions in all parts of the watershed benefit salmon recovery. She plans to compile the opportunistic actions completed in the first 5 y and evaluate them as a management strategy to compare what was actually accomplished with what might have been accomplished using a more systematic approach. Additionally, she plans to test the decision support system output by monitoring observed improvements in habitat and biological condition and comparing them to those predicted by the decision support system evaluation of the first 5 yr of opportunistic actions.

Guidance for other watersheds

Our approach of explicitly predicting the future conditions that would result from multiple possible watershed management strategies is easily transferable to other watersheds and even other species. In particular, the use of habitat models, which have been more thoroughly evaluated and tested, in combination with biological response models that predict the outcome of interest, fish population performance, but which are generally less precise, can dramatically improve decision making. Many of the specific models used in the Lewis River watershed example can be applied or adapted for use in other watersheds. Additional models that are available in other watersheds or that are created to quantify unique features of other watersheds could be added into the overall framework of creating and evaluating future landscapes.

Trade-offs between different types of actions, for example between fixing watershed processes in the upper watershed vs. opening up habitat in the lower watershed, will clearly be similar in many watersheds and the entire analysis may not need to be repeated. Moreover, conclusions about the models used to evaluate current and future conditions are transferable to other watersheds. For example, EDT model outputs, i.e., survival, productivity, were not particularly sensitive to the type and magnitude of actions modeled under this framework.

Any variety of additional watershed management strategies could be added to the framework, or our approach could be streamlined when there are few resources for the exercise. A simple and clearly organized table identifying alternatives, e.g., management strategies, and estimated odds of potential outcomes, i.e., outcome metrics, is a tremendous step toward good decision making. The user of our decision support system must then bring to the decision his or her own expertise, beliefs, risk-tolerance, and sociopolitical constraints. Combining predictions about habitat and biological response into a single score for purposes of ranking the possible watershed management strategies is possible; however, we strongly discourage this approach. Although apparently simplifying the decision into a simple rank of scores, a large amount of information is lost and details are hidden inside the scoring system.

There are some factors about our approach in the Lewis River basin that should be considered in applying insights from our results elsewhere. First, there is a series of large dams that prevent improvements in the upper watershed from being completely reflected in currently accessible fish habitat below the dams. Because plans are on the table to introduce fish above these dams, we modeled habitat conditions in these areas. In another basin without dams, the transfer of sediment, wood, and water from the upper parts of the watershed would be reflected in habitat conditions experienced by fish in the lower watershed. Second, detailed analysis of historical records indicated that the lower reaches of the Lewis River were historically dominated by deciduous rather than coniferous trees. We customized existing models to reflect this assumption. Such customizations may or may not be appropriate elsewhere. Historical and desired conditions should be considered explicitly in any new application of this suite of models. Third, there is a large and active volcano, Mount. St. Helens, in the watershed and it has provided a significant area of erosive and relatively unstable sediment in the upper reaches of the watershed that required customization of the sediment input models. And lastly, there is no estuary in our modeled watershed because the Lewis River drains into the Columbia River. Adding estuarine components in another watershed would be conceptually simple and might also enable more complex life-history models that could identify bottlenecks in population growth and help to identify the types of habitat that should be targeted for restoration.

Limitations of our approach

As in any modeling effort, assumptions are built into the final outcomes. We have tried to make these assumptions transparent and future research will include sensitivity analyses of key parameters. As described in the above examples, any implementation of these modeled results in the Lewis River or other watersheds should consider the potential impacts of model assumptions. Effects of some restoration actions are better captured by any one of our evaluation models than by the others. In-stream restoration, for example, can only be modeled by the remotely sensed capacity model and the EDT model. In predicting the impacts of any particular type of restoration action or in comparing effects of alternative restoration actions, the ability of the evaluation models to detect those actions should be considered. Of course, estimates of model precision for every model using the decision support system would add greatly to the value of the analysis, but it was not possible for this analysis.

We also would have liked to include a water temperature model in the decision support system. Because our ability to predict changes in water temperature regime as they are perpetuated downstream is limited without complex ground water input and hydrologic flow models, we chose not to incorporate this factor. Changes in riparian shade function can provide a partial surrogate for this information. No water quality models are incorporated in our approach because adequate data were unavailable. In the Lewis River watershed this omission likely has very little impact on our final outcomes because of the low human population density and low level of industrial or agricultural development. In another basin, models of water temperature and water quality may be essential additions.

To simplify presentation of results and the layers of model assumptions, we predicted the impacts of restoration in 50 y on a landscape that remains otherwise unchanged over those same 50 yr. A similar comparison of modeled strategies on a landscape that changes over time as a result of predicted human population growth and newly implemented policies is underway (Fullerton et al., *in press*). Incorporation of longer time horizons and natural disturbance regimes (e.g., Miller et al. 2003) would add additional reality to our decision support system.

And, finally, it is important to note that a scenario-based decision support system does poorly at addressing unexpected changes such as dramatic climate shifts, natural disasters, or unanticipated anthropogenic impacts. Unless the underlying models might generate unexpected changes or future scenarios include those changes, they will not be captured. Our approach can, however, be used to create and maintain conditions that will be most robust to catastrophic events, e.g., availability of a wide diversity of aquatic habitats that are spread across the landscape.

The value of a decision support system

The value of the decision support system is in the identification of realistic alternatives, the estimation of potential outcomes, and the organization of that information. By providing suites of predictions about the performance of multiple watershed management strategies, there is objective information on which to base critical management decisions. The process increases accountability in decision making while allowing subjective information such as belief in outcome from particular models or willingness to take certain kinds of risks. Users of this type of decision support system can make explicit trade-offs between spatial allocation of funds or allocation between actions that might benefit particular species or habitat types. With the structure of the decision support system, trade-offs are transparent to those impacted by the decision or tasked with implementing the watershed management strategy. The use of multiple models increases the robustness of the decision making process and reduces reliance on any one model. Tools for making robust and transparent trade-offs will be essential as pressure to balance the competing habitat needs of multiple species increases.

Responses to this article can be read online at:
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APPENDIX 1. EDT Translation Model We used the EDT model (Mobrand Biometrics 2004) in two different ways in this analysis. The first use of the EDT model was to generate a restoration strategy based on the reach level restoration and preservation prioritization output from EDT (Table A1 and A2). The second use of the EDT model was to evaluate the future landscapes. Using EDT to evaluate future landscapes required a translation between restoration actions and EDT input data (Table A3).

EDT Translation Model

We used the EDT model (Mobrand Biometrics 2004) in two different ways in this analysis. The first use of the EDT model was to generate a restoration strategy based on the reach level restoration and preservation prioritization output from EDT (Table A1 and A2). The second use of the EDT model was to evaluate the future landscapes. Using EDT to evaluate future landscapes required a translation between restoration actions and EDT input data (Table A3).

Table A1. The prioritization system for allocating funds to EDT reaches based on EDT output. Fifty percent of available funds were designated for restoration and 50% for protection. The same reach-level prioritization system was used to allocate funds independently for restoration and for protection.

Basis for Prioritization	Prioritization Notes
EDT model rankings for restoration or protection benefit	Select the reaches with the highest EDT restoration or protection benefit ranking If funds remain after treating all reaches identified as high priority, move to the reaches identified as intermediate priority.
Reach type: Spawning versus non-spawning reaches. Mainstem versus tributary reaches	Start with the spawning reaches. If funds remain after all high priority spawning reaches are treated, move to high priority mainstem reaches
Reach location	Within the high priority spawning (or migration) reaches, select the most upstream reach first.

Table A2. Translation from EDT model output for current conditions within each reach prioritized for restoration or preservation to the EDT watershed management strategy. Fifty percent of the funds were spent on restoration actions. Habitat attributes identified by EDT, by reach, as the most important were "fixed" first. Numbers in each cell represent the prioritization of restoration actions within each row. If there were two habitat attributes that were most limiting, we started with the cheapest problem to fix. All protection funds were spent on riparian protection or restoration. If the current riparian condition was good (as rated by the remotely-sensed riparian model in Table 4), riparian conditions were protected. If the current condition was fair or poor (as rated by the remotely-sensed riparian model in Table 4), riparian conditions were restored.

	Restoration Actions				
EDT Habitat Attribute	Restore Riparian	Decommission Roads	Remove Barriers	Restore for Spawning	Restore Floodplain[a]
Key Habitat				1	2
Temperature	1				
Sediment Load	2	1			
Obstructions			1		
Habitat Diversity					1
Food	1				
Flow	1	2			
Chemicals	1[b]				
Channel Stability	1	2			

[a] Only areas that historically had floodplains could be treated with floodplain restoration.
[b] If the habitat element was chemicals, riparian areas were only treated if the uplands were currently classified as agricultural or urban land-use.

Table A3. Model used to translate conservation actions in management strategies into data in a format ready to be used as inputs by the Ecosystem Diagnosis and Treatment (EDT) model. All actions were subject to 4 constraints: (1) the proportion of each EDT reach affected by a strategy was equal to the proportion of affected SSHIAP reaches comprising an EDT reach; (2) new EDT scores affected by conservation actions were constrained between patient and template scores and trended toward the template; (3) actions only affected scores if there was a potential for change; i.e., patient – template not equal 0; and (4) if >1 actions each changed EDT scores, only the largest was registered if effects were in the same direction but the sum of effects was registered if effects of actions had different directions. Abbreviations used are as follows: pΔ = potential for change; p(reach) = proportion of the EDT reach affected; ↑ = improve score. Conditions: †1 if any part of riparian area was originally urban and at least 50% of the reach is protected/restored; †2 also improve the next downstream reach in the same way; †3 if LWD or PFC function improves.

EDT Attribute	Decommission Roads	Protect or Restore Riparian	Restore Floodplain Connectivity	Restore Spawning Habitat
Bed Scour	Scour Depth is estimated directly from the modeled 2.3 year flood flow as Depth = 10*sqrt(flood discharge/bankfull width) (from Emmett and Leopold 1965), then converted to EDT ratings.			
Embeddedness	↑ score by p(reach) where roads are restored * Δ in % covered (as estimated based on road density).	↑ score by p(reach) restored.		New score is the p (reach) restored/ protected * pΔ.
Diel Variation in Flow		↑ score by ½ p(reach) where riparian area was urban * pΔ.†1		
Fine Sediment Deposited	↑ score by p(reach) where roads are restored * Δ in % fines (as estimated based on road density)* 1.34.			
High Flow	High Flow was calculated as the %Δ in modeled 2.3 year flood flow from historical, and then converted to EDT ratings.			
Large Woody Debris Recruited		New score is the p (reach) restored/ protected * pΔ.†3		New score is the p (reach) restored/ protected * pΔ.†3
Miscellaneous Toxic Wastes		↑ score by p(reach) where riparian area was urban * pΔ.†1		

(con'd)

Monthly Max Temperature		New score is the p (reach) restored/ protected * pΔ.[†2]		
Nutrient Enrichment		↑ score by p(reach) where riparian area was agriculture * pΔ.[†1]		
Channel Confinement resulting from hydrological modifications			New score is the p (reach) restored/ protected * pΔ.	
Off-Channel Habitat			↑ score by p(reach) where floodplains were restored * pΔ.	
Riparian Functions		New score is the p (reach) restored/ protected * pΔ.	New score is the p (reach) restored/ protected * pΔ.	
Small Cobble-Dominated Habitat				New score is the p (reach) where spawning habitat is restored * pΔ.
Turbidity	↑ score by p(reach) where roads are restored * 0.3 * Δ in road density.	↑ score by p(reach) restored * 0.3.		