

Reconciling Fisheries with Conservation in Watersheds: Tools for Informed Decisions

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Introduction

Watersheds capture and deliver freshwater to streams, rivers, wetlands and lakes. They are fundamental landscape units for freshwater fisheries because they govern the characteristics of the annual hydrograph, the configuration and physical features of stream channels, and the input of organic matter and nutrients. Watersheds are also where we live, grow crops, and create various forms of industry. As the world's population grows, competition for water and the ecological goods and services that water provides grows more intense. Between 1900 and 1995, global consumption of freshwater rose sixfold, about twice the rate of population growth (UNEP 2000). At the same time, freshwater capture fisheries remained at a high level and aquaculture continued to increase (Figure 1). The result is an increasing conflict between water for fisheries and water for other human uses, with native freshwater biota becoming imperiled at an increasing rate (Table 1). So important is the need to develop sustainable water policies that the United Nations General Assembly in De-

cember 2003 proclaimed the years 2005–2015 as the International Decade for Action, “Water for Life,” which began with World Water Day, 22 March 2005.

Even as ecologists recognize the importance of maintaining and restoring aquatic productivity through natural processes such as flooding, there will be increased pressure to remove water for agriculture, industry, and human consumption, to isolate rivers from their floodplains in order to maximize the land area available for development, and to impound rivers for power generation, flood control, navigation, and recreation. With so many societal conflicts, maintaining productive watersheds for fisheries while ensuring adequate water supplies for other uses will be an enormous undertaking in the 21st century (Naiman et al. 1995). Major challenges will include protecting currently productive habitats and restoring damaged ones, developing accurate forecasting and decision support tools, implementing monitoring programs to track fish population status and evaluate management actions, overcoming the inertia of ineffective watershed governance, and coping with climate change. In almost every case, policy-

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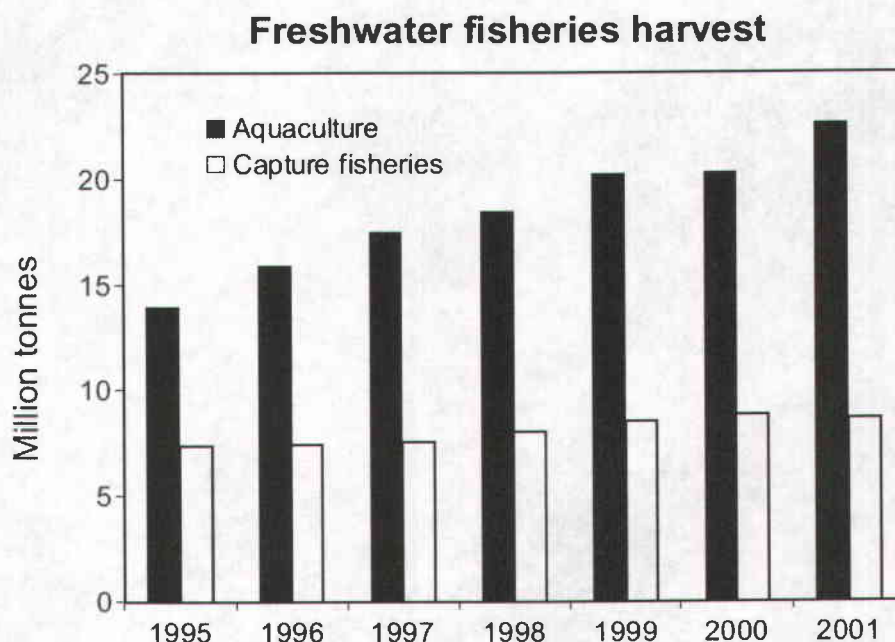


Figure 1. Worldwide freshwater production of fishes, crustaceans, mollusks, and so forth., from aquaculture and capture fisheries from 1995 to 2001. Data source: Food and Agricultural Organization of the United Nations (Vannuccini 2003) <http://www.fao.org/fi/trends/overview/2001/commodit/overview.asp>.

Table 1. Fresh water is rapidly becoming a natural resource in critical supply worldwide. The need for abundant, clean water for fisheries must be considered in a larger context of societal issues (sources: World Wildlife Fund, United Nations Environment Programme, and The Nature Conservancy).

Freshwater ecosystems	1% of the earth's surface; 40% of the world's known fish species
Status of freshwater biota	50% in decline over last 30 years; 20% of fishes have become extinct or are at significant risk of extinction
Estimated annual value of ecological services produced by fresh water	US\$6.6 trillion
Pollution	Over 90% of wastewater is discharged untreated into rivers and streams in developing countries; 80% of the pollution load in the ocean originates from activities in watersheds
Annual human deaths from poor water quality	5–7 million (10 times the number killed in wars)
People facing moderate to high water scarcity	Currently one-third of earth's population; by 2050, an estimated 7 billion people in 60 countries will face water shortage

makers will be faced with balancing the ecosystem needs of fishery resources with the need for drinking water, sanitation, agriculture, commerce, and recreation. Informed policies emerge when managers fully understand the tradeoffs between difficult choices.

In this paper we focus on some tools that can help managers find the balance between water and habitat for fisheries and water for other purposes. Although "scale" is important in watershed management—it provides a spatial and temporal context within which the effect of a policy can be judged—we use the term watershed without reference to a particular size or time interval because space and time have different meanings in different management settings. Our objective is to discuss concepts and tools that be used to bring complex, often uncertain, watershed information to managers in a way that facilitates sound decisions, irrespective of the size of the watershed in question.

Ecosystem Management Plans for Watersheds

Managing aquatic ecosystems to maintain a level of productivity sufficient to support sustainable fisheries means ensuring that the components of the watershed (its biological communities and physical environments) and the processes that maintain those components (for example, floods, erosion, and inputs of organic matter) are protected against anthropogenic changes that reduce or eliminate some components or strongly alter key processes. In many watersheds the emphasis has been to restore selected components such as habitat structure without regard to the processes that created them. The slogan "If you build it, they will come" seems to have influenced many restoration decisions in freshwater. While it is true that mitigation can be an important part of watershed restoration, mitigated habitats

alone rarely achieve sustainable, productive freshwater ecosystems without adequate provisions for the processes that created them in the first place. The problem is that some of those processes may be incompatible with other societal objectives such as flood control or wildfire suppression. To address this dilemma, ecosystem management plans for watersheds often attempt to balance natural processes with some controls on these processes to protect human development.

Balancing watershed processes that support fisheries with the protection of other water uses leads to policy decisions that vary from location to location. Policymakers need data to make informed choices, so ecosystem management plans should contain basic information that facilitates a clear understanding of the current status of the watershed and provides a means evaluate tradeoffs. The types of information should include:

1. An assessment of the overall condition of the watershed, including the location and quality of important aquatic habitats and an estimate of the range of conditions that existed prior to anthropogenic change;
2. A summary of key ecological processes that contribute to the full spectrum of habitats that would occur naturally in the area;
3. The type and location of land and water use actions that are and are not compatible with those processes;
4. Strategies for restoring damaged aquatic habitat which allow the processes to operate to some degree without continued, expensive intervention; and
5. Plans for adequately funded monitoring programs that provide timely feedback so ineffective actions can be corrected.

These goals are easy to state but exceedingly hard to achieve, and failures far outnumber successes (Collins and Pess 1997). "Ecosystem management" has become a popular term applied to many natural resource policies often without a common understanding of its goals (Yaffee 1999) or a real commitment to make it work (Healey 1998).

The difficulty in blending fisheries objectives with other land and water use objectives in watersheds stems from the effort and expense needed for the five elements noted above, resulting in one or more of these elements being inadequately addressed. In most cases the data needs are beyond the capability of a single organization and collaboration at multiple governmental and societal levels is required. Many watershed councils have been formed over the last three decades to coordinate the management of local and regional fisheries as well as other beneficial uses of water within a watershed (von Hagen et al. 1998). Watershed councils are usually self-generated by members of the local community who have grown tired of socially disruptive conflicts between fisheries and other water uses. Some watershed councils have been successful in reducing conflicts and in making genuine progress towards conservation; others have made few substantive changes (National Research Council 1996).

It is our belief that the failure of many ecosystem management plans to yield an improved balance of fisheries with other watershed uses is also caused by a lack of appreciation of the full range of ecological and societal values provided by clean water. In addition to supporting fisheries, clean water is necessary for human consumption and sanitation as well as for agriculture, industry, and recreation, yet these values are rarely presented in ecosystem management plans in a way that allows policymakers to understand

the full consequences of different management decisions on water for fish and water for other uses. The majority of environmental protection plans tend to be narrowly focused on a particular type of development (e.g., forest management or industrial waste discharge) without adequately considering the cumulative effects of different land and water uses at the scale of an entire watershed. Improvement of conservation practices in one type of development can easily be masked by continued habitat degradation from another type. Ecosystem management plans for watersheds will be more effective if they consider all potential impacts and not be constrained to one type of land or water use, and for plans to be successful at this scale, all major watershed stakeholders should participate in data gathering and evaluating the effects of past and future actions.

Watershed Analysis

Where implemented, landscape scale strategies that address the cumulative effects of different actions on freshwater ecosystems have often relied on formalized procedures designed to satisfy information needs (1) and (2), above. These procedures have been termed "watershed analysis," "watershed assessment," or similar names (Beechie et al. 2003). Time and expense of watershed analyses are usually related to the size of the area in question. Relatively small watersheds (4,000–20,000 ha) can be characterized in a few months, but very large drainage areas usually require several years of data collection and analyses.

One example of such an assessment is the Interior Columbia River Basin Ecosystem Management Project (ICBEMP), in which a number of U.S. agencies launched an ambitious effort to characterize the 500,000 km² Columbia River Basin in western North America. The Columbia River was histori-

cally one of the most productive salmon rivers in the world, but by the mid-1990s a number of its salmon stocks were at risk of extinction and formally protected under the U.S. Endangered Species Act (ESA). The goal was "to develop and then adopt a scientifically sound, ecosystem-based strategy" for managing all federal lands within the river basin (U.S. Department of Agriculture, Forest Service 1996), including a strategy that would protect fisheries resources while allowing for other land and water uses. The assessments produced a wealth of important aquatic habitat data at a very large scale, and clarified dramatic and persistent alterations to aquatic biodiversity across the watershed (Figure 2). These scientific databases will remain useful to decision makers responsible for evaluating risks and benefits of various management alternatives, even in the face of shifting social values or policies (Lee 1993).

Significant impediments can stand in the way of crafting workable, balanced management plans, including conflicting watershed resource values, opposing perceptions of desirable aquatic habitat, divergent institutional goals, and various political pressures. In the case of the ICBEMP project, the scientific assessment was completed and a preferred management option was selected, but the project never concluded with a binding agreement. One major stumbling block was the inability to reconcile an emerging scientific view that watersheds are dynamic and rivers should be managed for a natural range of conditions in order to maintain habitat diversity objectives, with the traditional view that watershed features and aquatic habitats should meet fixed environmental standards. The participants in the project could not reach consensus on the future conditions desired for the watershed. We conclude that a better appreciation for ecosystem processes is needed so that realistic expectations for future habitat conditions can be developed.

Natural Disturbances and Watershed Productivity

It is becoming increasingly apparent that reconciling fisheries with conservation in watersheds will require a new perception of the role of natural disturbances. Natural disturbances such as wildfires and floods often result in short-term damage to aquatic habitat, but over longer periods they are the source of many of the physical elements (coarse sediment and large wood) needed for productive riverine habitats (Reeves et al. 1995; Weins 2002). However, natural disturbances are unpredictable and can cause problems for other land and water uses, and societal needs usually dictate that disturbance effects be managed. Floods are controlled by damming or by isolating rivers from their floodplains with levees, wildfires are aggressively suppressed, and various methods are employed to capture and prevent sediment and trees (often assigned the uncomplimentary term "debris") from being carried by streams and rivers to areas where they could harm life and property. Thus the need to control natural disturbances can conflict directly with managing productive watersheds for fisheries.

Two questions are at the heart of attempts to reconcile a dynamic, disturbance-based view of watershed management with society's desire for predictability and protection from severe disturbance events. First, is it possible to maintain watershed productivity for fisheries while severely restricting the effects of natural disturbances? Second, is it possible to allow uncontrolled natural disturbance in part of the watershed that could contribute to habitat benefits throughout the entire drainage network? Control of natural disturbances interrupts long-term processes that create and sustain aquatic habitats in watersheds, leading to reduced habitat diversity (Beechie and Bolton 1999). Historically, artificially created habitats have been the most common method

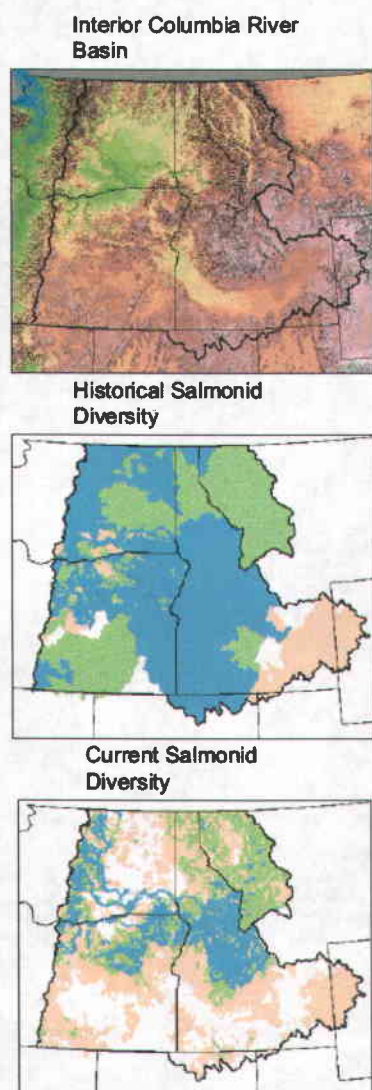


Figure 2. The portion of Interior Columbia River Basin (upper) in the USA, the inferred historical diversity of important salmon and trout species prior to the mid-19th century (middle), and the current diversity of salmonids in the same area after about 150 years of watershed development (lower). Dark shading indicates greater abundance and species diversity; light shading indicates low abundance or diversity; no shading indicates absence of native salmonids. Very large graphical presentations such as these illustrate the widespread extent of population declines and also help identify locations where fish communities are relatively healthy. Data source: United States Department of Agriculture, Forest Service (USDA Forest Service 1996) http://www.icbemp.gov/spatial/pubdoc/abbrev_sum/html/highlighted.shtml.

of mitigating the loss of disturbance-related habitats and ecosystem functions. Engineered habitats, however, have rarely replaced the full range of conditions that have been lost as the result of attempting to control natural disturbances in aquatic ecosystems (National Research Council 1992; Bisson et al. 1997), and freshwater habitat substitutions have never succeeded in fully mitigating fishery losses at the population level (Hilborn and Winton 1993; Roni et al. 2002). Replacing the range of conditions created and maintained through the natural disturbance regime by artificial habitats remains beyond the capacity of current technology. Nevertheless, artificial habitats may be the only option in very heavily developed watersheds, with the caveat that they cannot duplicate natural conditions.

The question of whether it is possible to achieve a full range of habitats by setting aside parts of a watershed where natural disturbances are permitted to occur, or by deliberately conducting management activities to emulate natural disturbances, remains largely unanswered. Parks and land reserves serve as de facto natural disturbance areas, but very often wildfires are suppressed, erosion is controlled, and floods are restrained if they potentially harm human dwellings or special features within reserve areas. There is a trend toward allowing disturbances such as wildfire to behave naturally in many parks. Such has been the case with fires in national parks of North America, where a policy of allowing some naturally-caused wildfires to burn freely as an ecosystem process has been in place for over two decades (<http://www.fireplan.gov/>; http://collection.nlc-bnc.ca/100/200/301/parkscanada/fire_in_ef/Fire_e.htm). This has undoubtedly resulted in watersheds with a greater diversity of vegetative communities and aquatic habitats, but many watersheds have been so thoroughly altered by logging, grazing, cultivation, and fire and flood suppres-

sion (Figure 3) that simply abandoning a policy of aggressive controls and allowing natural disturbances to take place unhindered may result in environmental effects far more severe than intended (Hessburg and Agee 2003). Landscapes that have been extensively altered may need to be "prepared" for natural disturbances by returning certain watershed features

such as native forests to conditions more like the ones existing prior to development (Figure 3).

The need to reconnect large alluvial rivers with their floodplains in order to maintain natural functions, and the simultaneous need to protect infrastructure such as roads, has led to innovations in river engineering. Historically,

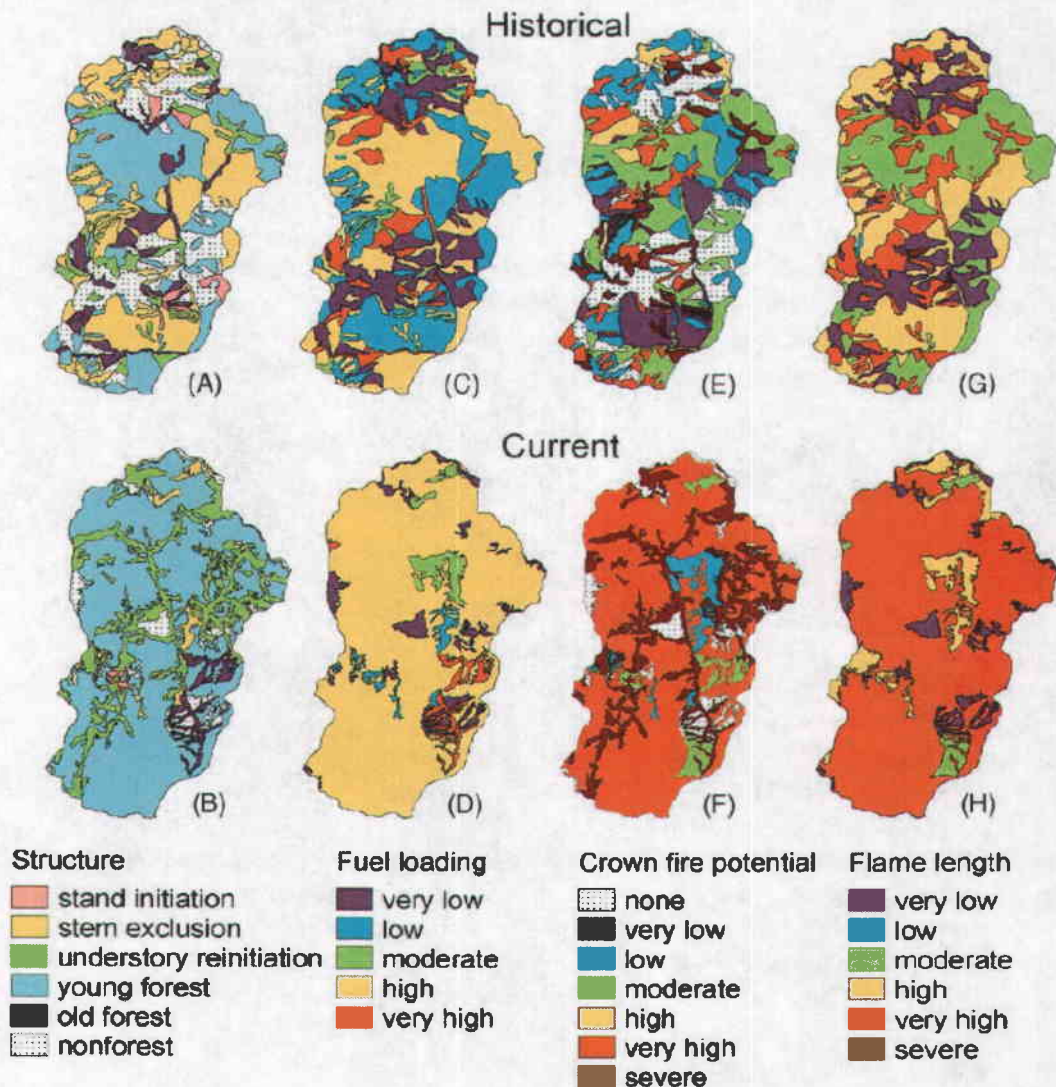


Figure 3. Forest conditions in the Peavine Creek watershed of northeast Oregon, USA, circa 1800 (historic) and 2000 (current) showing the high patchiness and diversity of pre-development forest stands and their vulnerability to wildfire, versus the relatively simplified stands and vulnerability to severe fires that currently exist after decades of logging, grazing, and fire suppression. From Hessburg and Agee (2003) with permission.

streambank protection projects and levees utilized primarily large rock to reduce streambank erosion and protect human developments. A restoration technique now popular in many areas is to use large wood instead of rock, and this approach combined with floodplain conservation easements has helped create more natural riverine habitats. In addition, functional floodplains are now being recognized as a benefit to society because of their ability to attenuate peak flows during severe storms and reduce flood damage downstream. The long-term benefits of initial projects are yet to be determined, but early results demonstrate improvements to aquatic ecosystems and reduced damage from flooding using streambank materials that would normally exist in floodplains (accumulations of large wood) combined with levee removal in certain areas where flooding will not damage infrastructure (Abbe et al. 2003).

The Colorado River of western North America is one of the most highly regulated rivers in the world, with large water withdrawals and daily water fluctuations caused by hydroelectric power generation contributing to a radically altered hydrograph. Nearly all of the native fishes in the lower Colorado are at risk of extinction and water diversions have been so extensive that the marine fishery in the upper Gulf of California, into which the Colorado River drains, has collapsed. In 1996, an experimental flood was generated from Glen Canyon Dam to help recreate sand bars in the Grand Canyon that were important spawning and rearing habitats for several fish species. Although the magnitude and duration of the experimental flood was quite modest relative to preimpoundment spring floods (Andrews and Pizzi 2000), new sand bars were created and benefits of the flood for fisheries clearly outweighed drawbacks. In this case, an anthropogenic disturbance designed to simulate natural flooding provided the eco-

system processes needed to maintain fish habitat. Other studies have shown that managed disturbances can be effective tools for controlling unwanted invasive riparian species (Sprenger et al. 2002). Deliberately caused disturbances, however, are politically hard to implement and public concerns over negative or unintended consequences of the disturbances often limit these experiments to relatively small scale, short duration events. Additionally, the benefits of managed disturbances may not always be realized. When water was released from Glen Canyon Dam to recreate another flood in November, 2004, preliminary evidence indicated the abundance of juvenile endangered fishes dropped the following spring. Investigators noted in a news interview that cold water released from the dam was well below the preferred temperature range for spawning by the endangered humpback chub *Gila cypha*, whose population of juveniles declined 63% after the 90-h flood release (<http://msnbc.msn.com/id/7126248/>). Because few large experiments such as the Colorado River simulated floods have been studied, it should be made clear to policymakers that the benefits of deliberate anthropogenic disturbances for fisheries, like those of artificial habitats, may be quite uncertain.

Seeing the Big Picture

One of the most challenging issues in reconciling fisheries with conservation in watersheds is educating policy makers and stakeholders about the importance of placing an activity that could affect fisheries in a larger context, as there is a tendency to view a proposed activity as influencing only its immediate surroundings. Development of new methods to display a variety of landscape-scale information that is spatially explicit has provided scientists, fishery managers, and policy makers with the ability to view watersheds and aquatic resources in ways that

have not been possible before. In fact, we believe the advent of geographic information system (GIS) technology, perhaps more than any other new development, has catalyzed our ability to think of watersheds, rather than individual project sites, as basic management units. In addition to computer-based mapping, other remote sensing tools such as satellite photography and laser imagery have generated an enormous amount of data and images, and much of this is readily available on the internet. Many technologies originally developed for military applications are being adapted to watershed management.

Comparison of historic and current conditions in watersheds is an important analysis step that documents habitat loss and identifies fisheries restoration targets (Beechie and Bolton 1999), and GIS technology has facilitated such assessments over larger areas and with greater detail than were previously possible (Collins et al. 2003). It is often necessary to recreate historic data layers with the aid of old field notes, river navigation charts, land ownership and other legal records, topographic and geological surveys, and drawings and photographs. Once this information is compiled, comparisons of historic and current conditions become possible, and relative confidence can be ascribed to the description of watersheds prior to development. Few such analyses were completed prior to the widespread availability of GIS (e.g., Sedell and Luchessa 1982; Beechie et al. 1994), but many such comparisons have been completed in the last decade and have been the focus of the initial assessment phase of watershed analysis. An example is shown in Figure 4, in which the condition of the drainage network and associated land development in Washington State's lower Snohomish River and its two major tributaries, the Snoqualmie and Skykomish Rivers, are contrasted between 1870 and 1990 (Collins et al. 2003).

It is important for stakeholders to understand the likely consequences of different watershed management scenarios, but long-term forecasting is never certain and outcomes are hard to visualize at this scale. An important use of spatial analysis has been to project future conditions in watersheds and trends in aquatic habitat based on assumptions about population growth and alternative development strategies. In the Willamette River basin of western Oregon, USA, a consortium of agency and academic scientists, working with state and local land use planners, conducted an analysis of future changes using different development scenarios (Hulse et al. 2002). The Willamette Basin contains the richest native fish fauna in Oregon and has several high profile species (e.g., spotted owls, Chinook salmon *Oncorhynchus tshawytscha*) that are listed under the Endangered Species Act. The management scenarios were all based on an assumption that the human population would nearly double between 1990 and 2050, but that development patterns could follow one of three alternative trajectories:

1. *Plan Trend 2050*—a continuation of the current status quo (i.e., development would follow current plans and trends).
2. *Development 2050*—a future projection that emphasized agricultural and industrial development with a loosening of environmental regulations; and
3. *Conservation 2050*—a strategy that emphasized protection of important habitats for fish and wildlife while concentrating human development in smaller areas with a lower overall environmental impact.

The three trajectories were developed after consultation with local stakeholders and government agencies, and were considered to be feasible, realistic alternatives. Using economic

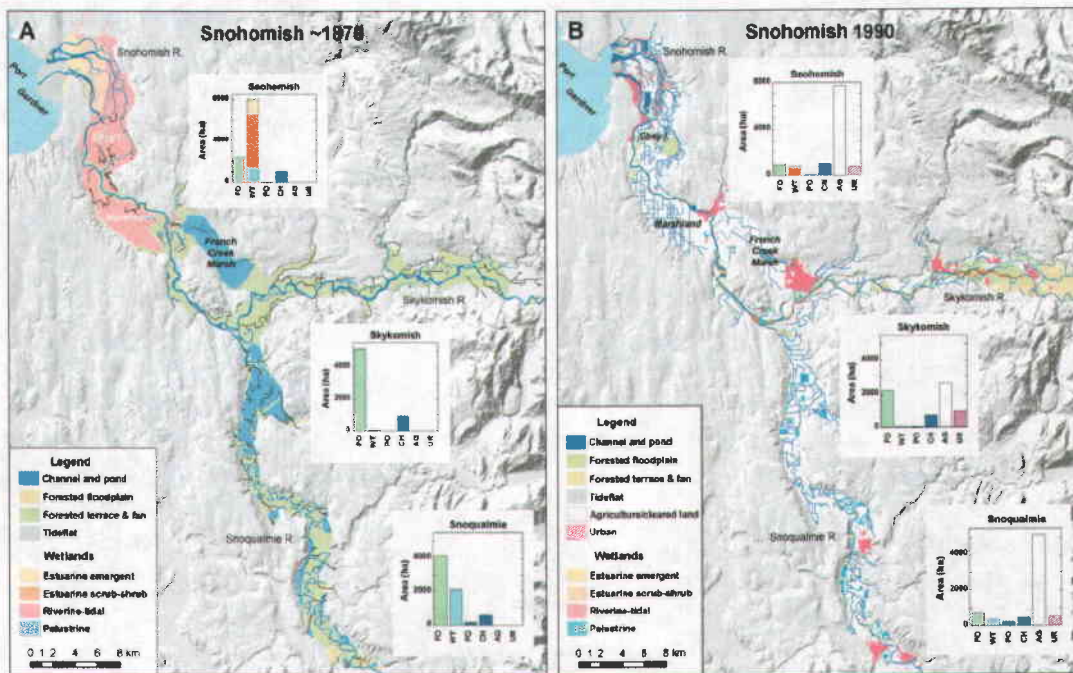


Figure 4. A. Stream channels and other aquatic habitats in the lower Snohomish River basin and its two major tributaries, Snoqualmie River and Skykomish River, circa 1870. Bar graphs show areas of FO = forested floodplains, WT = wetlands, PO = pond, CH = stream channel, AG = agricultural/cleared land, UR = urban. B. Conditions in 1990. From Collins et al. (2003) with permission.

forecasts, information on life histories and preferred habitats, and GIS tools the consortium generated projections of land cover and land use at 10-year increments. Figure 5 shows projected changes in land cover under the three scenarios (upper graph), as well as shifts in scores of multiple environmental metrics (lower graph). The analysis was able to combine complex maps, trends, and data sets in such a way that planning organizations could view the potential consequences of watershed management policies in ways that had not been possible before. For example, the development emphasis scenario resulted in significant losses of old-growth coniferous forest and both wildlife habitat and abundance, but the projections did not show much change in aquatic habitats or fish species richness relative to 1990 (Oregon has relatively strong regulations governing freshwater ecosystems).

Only the conservation emphasis scenario projected a return toward the predevelopment conditions that occurred circa 1850 (Figure 5), even with water extraction for human use forecast to increase 40–60% over current levels. This analysis has become the centerpiece of a state-sponsored Willamette Restoration Initiative and has been an effective public education tool.

The value of such predictions depends on accurate forecasts. The ability to simulate changes at large spatial areas over multiple decades requires models calibrated at scales appropriate to the analysis, a way of describing natural variation, and an expression of uncertainty in projected outcomes (Wissmar and Bisson 2003). Landscape models have enjoyed considerable popularity, but drainage networks pose unique modeling challenges

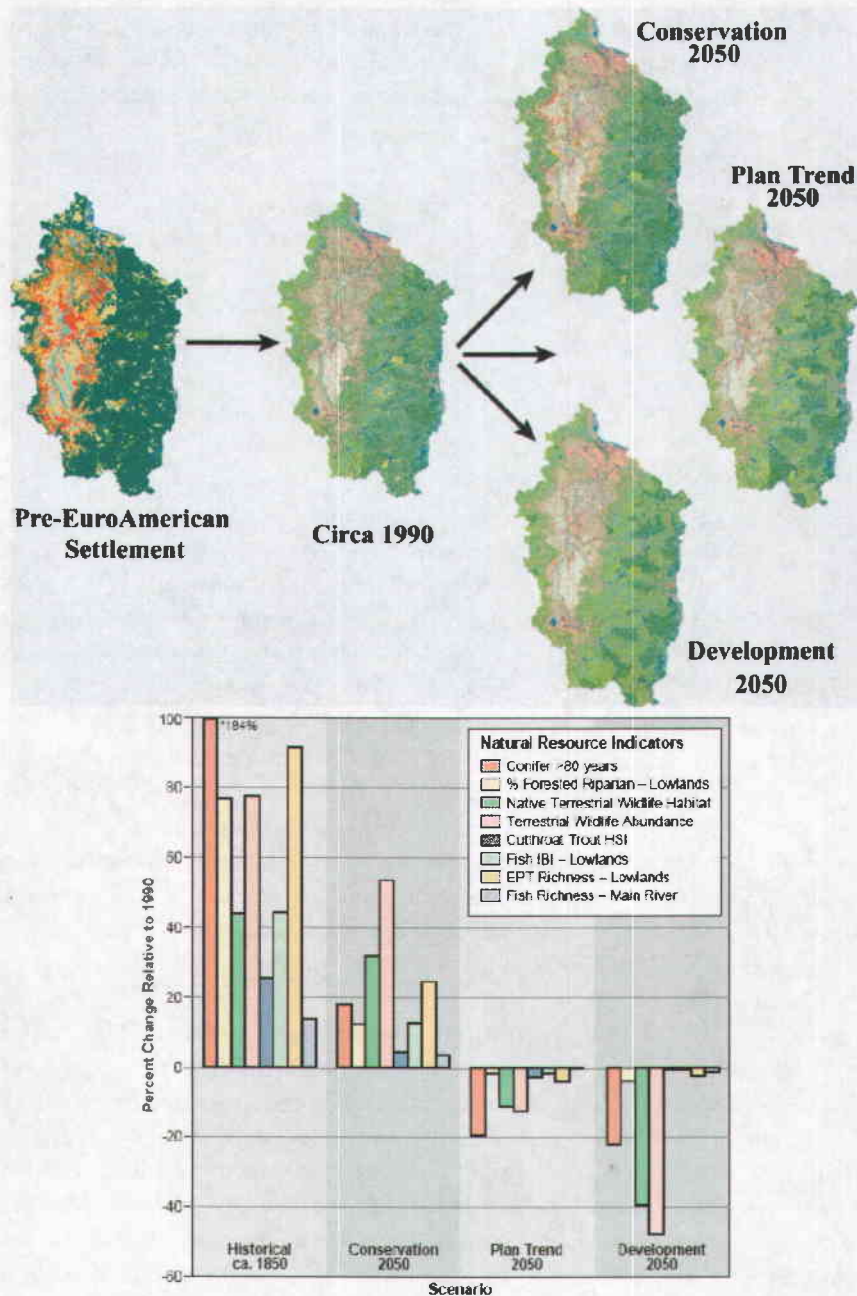


Figure 5. Upper: changes in land cover in the Willamette River Basin under three alternative scenarios, *Plan Trend 2050* (status quo), *Conservation 2050* (conservation emphasis), and *Development 2050* (development emphasis). Darker shading indicates coniferous forests of increasing age; lighter colors indicate meadows, shrublands, wetlands and floodplains. Lower: changes in eight environmental metrics over the 200-year period, including upland coniferous forests, riparian and lowland forests, wildlife habitat and abundance, cutthroat trout habitat (HSI), biotic integrity of lowland fish communities, and species richness of select macroinvertebrates and mainstem river fishes. From Hulse et al. (2000) with permission.

that require knowledge of spatial habitat heterogeneity, longitudinal and lateral connections within watersheds, abilities of aquatic organisms to adapt to change, and climate trends. Many of these considerations have been incorporated into a perspective termed "riverscapes" by Fausch et al. (2002), in which freshwater fisheries models will require data on spatial patchiness at multiple scales (drainage basin, stream segment, reach, channel unit, and microhabitat) as well as the preferred habitats and movement patterns of important species. So great is the need for new modeling approaches that can be coupled to spatially referenced data that we examine the topic in the following section.

Watershed Models

Decision making can be hampered if a watershed becomes engulfed in a "collision of models," where interest groups and agencies use models to advocate the conclusions that best support their interests and mandates. There are now at least three distinct approaches to modeling for decision support. These are *decision analysis*, *statistical*, and *expert system*, and it is important to understand the strengths and limitations of each model type.

Of the three approaches, decision analysis (e.g., Peters and Marmorek 2001) is most closely directed at providing management advice, and it is the most formal about factoring uncertainty into the analysis. This approach includes most "weight of evidence" models. The decision analysis approach has the potential to be the most useful to watershed decision makers but it is very difficult to implement successfully. Its success depends crucially on the engagement of the actual decision makers in framing the questions that need to be answered, identifying the watershed management options that are under consideration, and in defining the values put on

the various possible outcomes. Such engagement and communication is often difficult to achieve where there is fragmentation of decision-making authority.

The statistical approach (e.g., Kareiva et al. 2000; Wilson 2003) is the most classical of the three, and it can operate with a large degree of detachment from policy. It proceeds by testing hypotheses and estimating life history parameters with available data for fishes in the watershed. This has the advantages of clarity, rigor, and empirical objectivity. The limitation of this approach is that the scope of the questions that can be answered with satisfactory conclusiveness is restricted by the availability of data. In a domain that is data-poor, many pressing questions may go unanswered, and conclusions are strongly influenced by assumptions made in the analysis process. For example, Kareiva et al. (2000) and Wilson (2003) employed the same basic model to analyze restoration options for Columbia River salmon, but arrived at opposing conclusions regarding removal of large dams as a restoration action because of differing assumptions about how to represent the salmon life cycle in the model.

Expert system approaches (e.g., Mobrand et al. 1997) fill gaps in data with expert opinion. In the context of fisheries issues, expert opinion allows consideration of the most concrete menu of specific options for actual management. Expert opinion is, admittedly, a weaker basis for scientific prediction than is a mathematical relationship validated with an archive of quantitative empirical data (i.e., the statistical approach). It is important to recognize, however, that at the level of spatial resolution and environmental detail required to make fisheries management decisions at watershed scales, there are rarely any validated mathematical relationships for predicting reliably the effects of management actions on

fish, and there is usually no adequate data archive for deriving such relationships. However, the expert system approach may well be a reasonable and practical method for providing tentative answers to some watershed management questions that need to be addressed quickly.

There is another class of models that do not describe the behavior of fish populations but instead the physical processes that create fish habitats. Physical process models are just as critical to planning watershed conservation strategies as biological models. Whatever the fishery resources of concern, conservation and restoration efforts begin with an understanding of local and regional landform, hydrological and erosion patterns because these provide the physical template upon which management decisions are based. The observation that fish populations in freshwater are not uniformly distributed along drainage gradients but instead utilize preferred habitats ("hotspots") for different life history functions suggests that riverine fishes are often segregated into subpopulation units within the larger metapopulation of the river basin, with limited genetic exchange among subpopulations and with multiple life history strategies that spread the risk in an unpredictable environment (Schlosser and Angermeier 1995). Conservation of biological hotspots for aquatic communities and provision of ecological connections between productive areas has become an important paradigm in watershed management (Sedell et al. 1994; Angermeier and Schlosser 1995) and is generally considered necessary for protecting biodiversity. Within watersheds, some areas are likely to be productive most of the time, other areas may have little production (Pess et al. 2002), and some places may alternate between periods of high and low productivity as disturbance-recovery cycles play out over time (Benda et al. 1998).

Physical process models can help watershed managers assess the potential long-term risks and benefits of certain types of land use. For example, in the Mae Chaem watershed (3,900 km²) in northern Thailand, lowland residents are concerned that deforestation and conversion to agriculture by residents of the headwaters (Figure 6) would exacerbate flooding in the wet season and result in reduced dry season flows—both of which would be harmful to fish habitat and existing development. Using a large scale runoff model (Distributed Hydrology Soil-Vegetation model, DHSVM), streamflow under alternative future scenarios in which cultivated agricultural lands would be increased from the current 10% of the watershed area to 20% and 60%, were simulated based on real discharge data from 1996 to 1999 (Porranee Rattana- viwatpong and others, unpublished). Doubling the amount of land under cultivation from 10% to 20% of the watershed was predicted to cause a slight increase in peak flows and essentially no change in low flows, whereas increasing the amount of cropland to 60% would raise peak flows by about 25–50% and, surprisingly, also increase low flows by about 20–30%. Presumably the increased low flows would result from lower evapotranspirative water losses if forests were cleared from a substantial part of the watershed. Hydrologic modeling used in this way can provide new insights into the long term effects of land use changes, and pose testable hypotheses in an adaptive management context.

Conclusion

A variety of new techniques for characterizing watersheds and their aquatic resources are being explored, yet while new and innovative techniques provide information that provides a broader spatial and temporal context for policy decisions, they often cannot resolve

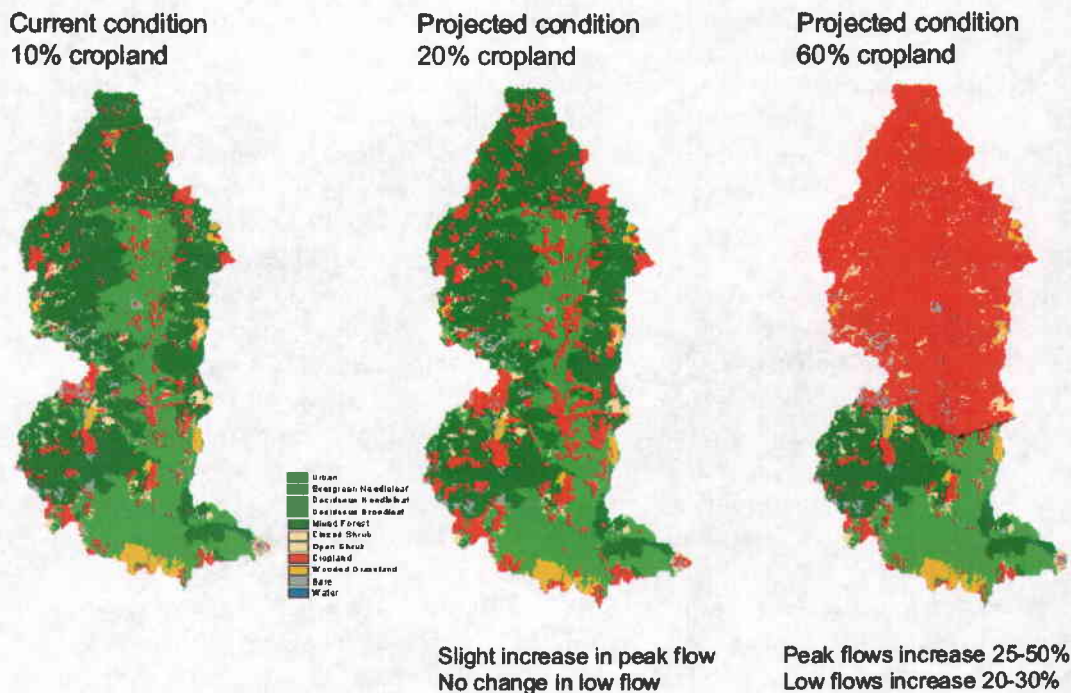


Figure 6. Land cover of the Mae Chaem watershed, northern Thailand, under current conditions and projected future conditions in which agricultural lands would be increased to 20% and 60% of the watershed area, respectively (Porranee Rattanaviwatpong, unpublished, with permission).

difficult natural resource tradeoffs (e.g., fish versus crops or electricity) nor can they address the fragmented management structure that results from the mismatch of watershed boundaries with ownership patterns and political jurisdictions. In many ways, these are the most vexing issues that challenge our ability to reconcile fisheries with conservation in watersheds. Given the precarious condition of the world's freshwater resources, however, real advancements in watershed management must emerge from a more useful blend of ecological and political disciplines.

Acknowledgments

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