
Evaluating the Biotic Integrity of Watersheds in the Sierra Nevada, California

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Abstract: *We developed a watershed index of biotic integrity that used whole watershed variables for metrics rather than site-specific variables. We used the index to evaluate the biological health of 100 watersheds in the Sierra Nevada of California. The index scores, which were based on various measures of distribution and abundance of native fish and frogs, indicated that 7 of the watersheds were in excellent condition (high biotic health), 36 were in good to very good condition, 48 were in fair condition, and 9 were in poor condition. The biggest factors contributing to low index scores were large dams and introduced fishes, although measures of road density and indicators of intensity of use of terrestrial habitats were also important. Large areas of the Sierra Nevada that were once fishless now contain trout in most waters, anadromous fishes are excluded from many streams from which they were once abundant, assemblages of native fishes have been disrupted, and ranid frogs have been extirpated from many areas. All watersheds in the Sierra Nevada have thus experienced loss of biotic integrity, but some have suffered much less than others. Evaluations of the biotic integrity of watersheds over wide regions can help managers set priorities for watershed-oriented systems of aquatic conservation and provide starting places for more-intensive studies.*

Evaluación de la Integridad Biótica de Cuencas Acuíferas en la Sierra Nevada, California

Resumen: *Un índice de cuencas de integridad biótica fue desarrollado, el cual utilizó variables paramétricas en vez de variables de lugar específico. El índice fue utilizado para evaluar la salud biológica de cien cuencas en la Sierra Nevada de California. El muestreo, el cual fue basado en varias medidas de distribución y abundancia de peces nativos y ranas indicaron que siete de las cuencas estaban en excelente condición (salud biótica), treinta y seis estaban de buena a muy buena condición, cuarenta y ocho estaban en favorable condición y nueve estaban en mala condición. Los factores más grandes que contribuyeron al bajo muestreo fueron represas grandes y peces introducidos, aunque medidas de densidad de carreteras, indicadores de intensidad del uso de comunidades terrestres, fueron también importantes. Grandes áreas de la Sierra Nevada que no tenían peces ahora contienen trucha en la mayoría de sus aguas, peces anadromos están excluidos de muchos arroyos, en los cuales ellos fueron una vez abundantes; comunidades de peces nativos han sido interrumpidas, y ranas de la familia ranidae han sido exterminadas de muchas áreas. Todas las cuencas en la Sierra Nevada, por lo tanto, han experimentado pérdida de integridad biótica, pero algunas han experimentado menos pérdida que otras. Evaluaciones de la integridad biótica de cuencas sobre regiones extensas pueden ayudar a establecer prioridades para un sistema de conservación acuática y proveer información básica para estudios más intensos.*

Introduction

In California, as in most temperate and arid regions of the world, aquatic biodiversity is being lost rapidly because aquatic ecosystems have been severely altered by

human activity (Moyle & Williams 1990; Moyle & Leidy 1992; Jensen et al. 1993; Leidy & Moyle 1998). Protection of aquatic ecosystems often lags behind that of terrestrial ecosystems because parks and preserves are usually focused on terrestrial features and often protect only fragments of watersheds, with little concern for the dynamic processes that maintain intact aquatic ecosystems (Moyle & Sato 1991; Doppelt et al. 1993; Noss & Cooperrider 1994; Frissell & Bayles 1996). A prime example

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of this problem can be seen in the Sierra Nevada, the mountain range that forms the backbone of California and supplies much of the state's water for human consumption. The major protected areas in the Sierra Nevada, such as Yosemite, Sequoia, Kings Canyon, and Lassen national parks, are at high elevations, and even in these areas dams and diversions on streams are common (e.g., Hetch-Hetchy Reservoir in Yosemite National Park). Below these protected areas, the land is under a mixture of private and public—mostly national forest—ownership, with private lands becoming more predominant at lower elevations. Most of the streams flowing through these lands are dammed, diverted, or altered in one way or another, and few watershed-oriented management efforts in the range cut across political and ownership boundaries. One of the key findings of the congressionally mandated Sierra Nevada Ecosystem Project (1996) was that "The aquatic/riparian systems [in California] are the most altered and impaired habitats of the Sierra," resulting in continuing extinction and endangerment of native fishes, amphibians, and aquatic invertebrates.

Moyle and Yoshiyama (1994) present conservation strategies for protecting aquatic biodiversity in California ranging from protecting individual species to managing landscapes or bioregions in an appropriate manner, including rehabilitation of degraded areas. They indicate, however, that the strategy most likely to provide widespread protection for aquatic biodiversity within the realm of political possibility is the development of a system of large watersheds in which protection of biodiversity is a high priority. Watersheds are good units on which to base conservation efforts for aquatic organisms because they are usually relatively easy to define and because they can contain a variety of species and habitats, depending on their size and location. For aquatic organisms, watersheds or groups of watersheds are also often the landscape units in which speciation takes place. In the Sierra Nevada, for example, five endemic subspecies of rainbow trout (*Oncorhynchus mykiss*) or cutthroat trout (*O. clarki*) were originally confined to single watersheds (Moyle 1976a). On a broader scale, the interconnected watersheds draining the west side of the Sierra Nevada (Sacramento–San Joaquin drainage) originally had only one widely distributed fish species, the speckled dace, (*Rhinichthys osculus*) in common with watersheds draining the east side of the range (Great Basin drainages).

A problem with the selected watershed approach to conservation is that it implies that watersheds can be systematically rated so that those with the highest biodiversity values can be the focus of whole-watershed protection efforts. Implicit in this approach is that not all watersheds can be protected equally, although from many perspectives universal watershed conservation and management is highly desirable (Doppelt et al. 1993). An example of the selected watershed approach is that of Frissell et al. (1996) for the Swan River basin in Montana. Using gap

analysis, they identified 15 tributary watersheds, four connecting river and lake segments, and seven wetland complexes to provide a network of potential aquatic reserves. We present an alternate method, a watershed index of biotic integrity (W-IBI), for identifying watersheds with high conservation potential over a much larger area, the Sierra Nevada. We present the results of the application of the W-IBI to 100 Sierra Nevada watersheds. To provide some indication of which factors have the largest negative impact on aquatic biodiversity, we also present the relationships between the W-IBI score for each watershed and broad measures of land and water use.

Methods

Watershed Scale

The first problem to be resolved for this analysis was which watershed scale to use. The standard system for identifying watersheds in California (California Department of Forestry and Fire Protection 1996), which we used, breaks each major drainage basin (e.g., the Central Valley) into major tributary systems called hydrologic units. Each hydrologic unit is divided into hydrologic areas, which are divided into hydrological subareas; these in turn are divided successively into super-planning watersheds and planning watersheds. There are thousands of watersheds in the latter two categories, but using them as the unit of analysis, although desirable, is not possible now because of a lack of site-specific information. We chose as the basic unit of analysis, therefore, the hydrologic subarea, occasionally using higher units if an area was not broken into hydrologic subareas. Our evaluation covered 100 watersheds (Fig. 1). We analyzed Sierra Nevada watersheds only in California because of the difficulty of obtaining equivalent data for the relatively small Nevada portion of the Sierra Nevada. The watersheds ranged in area from 4816 ha (a partial drainage on the California-Nevada border) to 382,669 ha (the Upper Owens drainage). Most (62%) of the analysis watersheds, however, were between 15,000 and 90,000 ha in area; 28% were larger than 90,000 ha and 10% were less than 15,000 ha. All watersheds within these categories were the forks of large rivers (e.g., the South Yuba River, North Fork Kings River) or drainages (e.g., Deer Creek in Tehama, Placer, and Tulare Counties) that drained directly into lowland basins such as the Sacramento River. From a human perspective, the chosen watersheds are well-defined units on the landscape and are often used as identifying units for watershed groups (e.g., Deer Creek Watershed Conservancy) or individuals (South Yuba Drainage; Snyder 1990). All were large enough so that watershed-oriented conservation activities would be likely to protect the native biota while allowing modest levels of human activity. An additional 34 watersheds were not evaluated because of in-

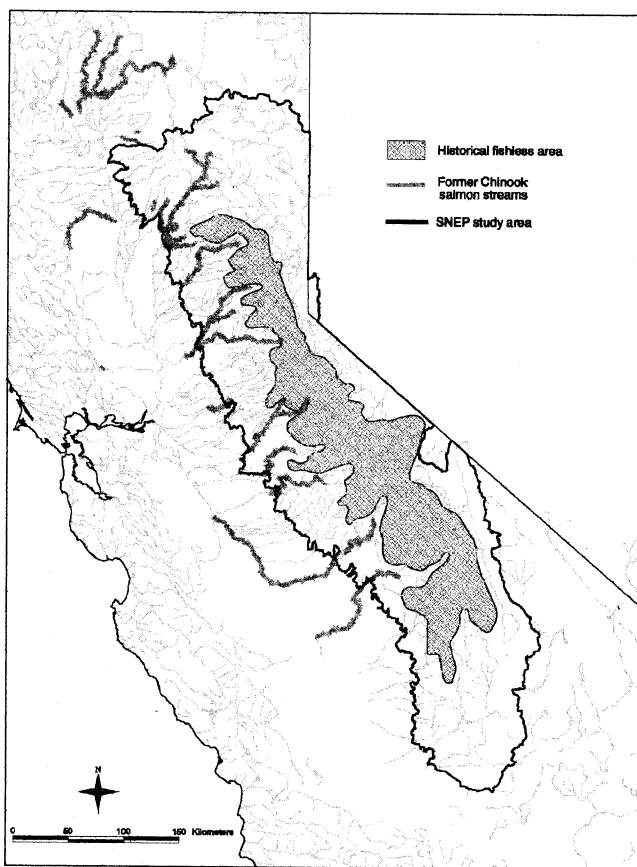


Figure 1. Approximate extent of original naturally fishless area of the Sierra Nevada and of river reaches from which anadromous fish are now absent as a result of dams. Most waters in the fishless area now contain trout.

adequate information on their aquatic biota. These watersheds were all at low elevations, small in size, mostly lacking permanent water, and on private lands with difficult access (Fig. 1). Nine of these watersheds marked the southern end of the Sierra Nevada Ecosystem Project area, 22 were in the foothills along the western edge of the boundary, and 3 were along the California-Nevada border. It is highly likely that if information were available (and there was permanent water present), they would have scored nearly the same as adjacent watersheds.

Index of Biotic Integrity

The second step in developing recommendations for a system of conservation-oriented watersheds in the Sierra Nevada was to rate the 100 watersheds using a modification of the index of biotic integrity (IBI) concept. An IBI is a measure of the health of streams that has been developed as an alternative to physical and chemical measures of water quality (Karr 1981, 1993; Karr et al. 1986). The idea is to combine a number of measures of fish commu-

nity structure and function into an index, on the assumption that the responses of an integrated community of fishes to changes in the environment would reflect both major environmental events (e.g., a pesticide spill) and more subtle long-term effects, such as chronic nonpoint source pollution and changes in land use.

Biotic integrity is defined as "the ability to support and maintain a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of the natural habitat of the region" (Karr & Dudley 1981). An IBI is a method of measuring this complex idea, and IBIs can be developed independently for different regions or streams. Indexes of biotic integrity are now widely used in the eastern United States, where fish communities are complex and made up largely of native species (Miller et al. 1988). For eastern streams it is possible to develop an IBI that uses 10–12 different measures (metrics) of the nature of the fish assemblage in the creation of the final index (Karr et al. 1986). In California the small number of native fishes in most streams makes development of complex IBIs with numerous metrics difficult (Miller et al. 1988). In fact, two measures, number of native resident fish species and abundance of native fishes, provide much of the information needed to determine biotic integrity as defined previously. In Sierra Nevada streams, if the fish communities are intact, the stream is likely to have a fairly natural hydrograph and the watershed is likely to be in reasonably good condition (Baltz & Moyle 1993). Native resident fishes are only part of the biotic integrity picture, however, especially in relation to water quality, so we developed a watershed index of biotic integrity (W-IBI) for Sierra Nevada watersheds that takes into account not only native fish assemblages but also the abundance of native frogs, the presence of anadromous fish, and the widespread introduction of trout into fishless streams. The W-IBI is different from typical IBIs in that it is watershed-oriented rather than being site-specific. Most IBIs are designed to evaluate biotic integrity at individual sampling sites, although distributions or averages of IBI scores can be used to evaluate larger areas.

The use of frog distribution and abundance as metrics is also different from other IBIs. Only ranid frogs were used for these metrics because at least one species of *Rana* was historically abundant in every watershed, and there is reasonably good distribution and abundance data available for them (Jennings 1996). Ranid frogs also seem to be unusually sensitive to environmental change. Other amphibians considered for metrics were "true" salamanders (*Ambystoma* spp.), newts (*Taricha* spp.), true toads (*Bufo* spp.), Pacific tree frog (*Hyla regilla*), and lungless salamanders (Plethodontidae), but they were not used because of a combination of incomplete distribution and abundance records, lack of natural occurrences in many watersheds, and the uncertain taxo-

nomic status of some forms. We also considered developing metrics based on aquatic reptiles (turtles, snakes) and stream invertebrates, but we lacked sufficient information to do so.

Metrics of Biotic Integrity

The W-IBI developed for this analysis included six metrics: native ranid frogs, native fishes, native fish assemblages, anadromous fish, trout, and stream fish abundance. Each metric was rated as 1, 3, or 5, where 1 is low (poor) and 5 is high (good), as has been done for other IBIs (Miller et al. 1988). The metrics were added and standardized to a 100-point scale because not all metrics could be used in all drainages.

NATIVE RANID FROGS

The foothill yellow-legged frog (*Rana boylei*), mountain yellow-legged frog (*R. muscosa*), Cascade frog (*R. cascadae*), California red-legged frog (*R. aurora draytonii*), and leopard frog (*R. pipiens*) are amphibians that are extremely sensitive to environmental change. Their disappearance from much of their native habitat in the Sierra Nevada is a cause for concern; their presence in a watershed is an indication that high-quality aquatic and riparian habitats still exist and that introduced bullfrogs (*R. catesbeiana*) are not present. We scored each of the 100 watersheds for this metric by means of information presented in Jennings and Hayes (1994), personal communications with M. Jennings, observations of our own, and, in a few cases, discussions with other biologists, especially for confirmation of scores. If there were no or just one or two recent records of frogs from the watershed we gave the watershed a score of 1. If the frogs were known to be present in multiple locations but were not particularly abundant, we gave the watershed a score of 3. If frogs were abundant and widely distributed in the watershed, we gave it a score of 5. For the most part, it was easy to place each watershed in one of the three categories.

NATIVE FISHES

The native resident fishes of the Sierra Nevada are highly adapted to natural flow regimes, and they tend to become depleted if the flow regimes are changed, especially by dams. This metric is based on general abundance rather than number of species because different watersheds for zoogeographic reasons differ naturally in number of native species. Scores for this metric are based on field notes of P.B.M. and studies such as Brown and Moyle (1993). Another important source of information was the data collected by the Wild Trout Program of the California Department of Fish and Game. In many instances, agency biologists familiar with a watershed were

consulted as well. The watersheds are large enough for all native resident species to complete their entire life histories within the watershed, and scoring was based on sampling from multiple sites within each watershed. A watershed was scored as 1 if native fishes were absent or rare in its waters, typical of many low-elevation streams, or if its waters were originally fishless but now contained fish (including species native to lower elevations). If native fishes were present in only part of their probable native range within a watershed but were still fairly easy to find, the watershed was scored 3. If native fishes were found throughout the watershed with a distribution and abundance approaching their presumed historic levels, the watershed was scored 5. When conditions in a watershed appeared to be intermediate between two criteria, an intermediate (2, 4) score was given. The historic native range was usually easy to infer because typically the upstream-most populations were the ones most likely to persist into the present. Distribution maps of the native species are available over the internet at <http://ice.ucdavis.edu/aquadiv/fishcovs/fishmaps.html>.

NATIVE FISH ASSEMBLAGES

One of the best indications of high-quality aquatic environments in California is the presence not only of native species but also of groups of species co-occurring in their natural assemblages of three to six species (Moyle & Yoshiyama 1994). Some of the native fish species can persist indefinitely in altered habitats and in the presence of exotic fishes, whereas others cannot (Moyle & Williams 1990). This metric was scored based on information from the same sources that were used in the previous metric, using assemblages largely defined in Moyle (1976a), except that assemblages containing only trout (Salmonidae) were excluded. To score a 1, the assemblages in a watershed had to be made up largely of non-native species and/or be missing some of the native species that were once present. For a 3, the watershed had to have remnants of its native fish assemblages, in isolated pockets of habitat and/or had to contain one or more nonnative species. For a 5, the assemblages in the watershed had to be largely intact, a rare condition. Intermediate scores were also awarded a few times for this metric.

ANADROMOUS FISHES

Chinook salmon, steelhead rainbow trout, and Pacific lamprey (*Lampetra tridentata*) were once important parts of aquatic ecosystems at low to middle elevations in western Sierra Nevada streams from the Kings River (Fresno County) north. Their exclusion by dams from much of their former habitat has significantly altered the stream communities of which they were once part (Fig. 2). We scored this metric based on estimates of past and

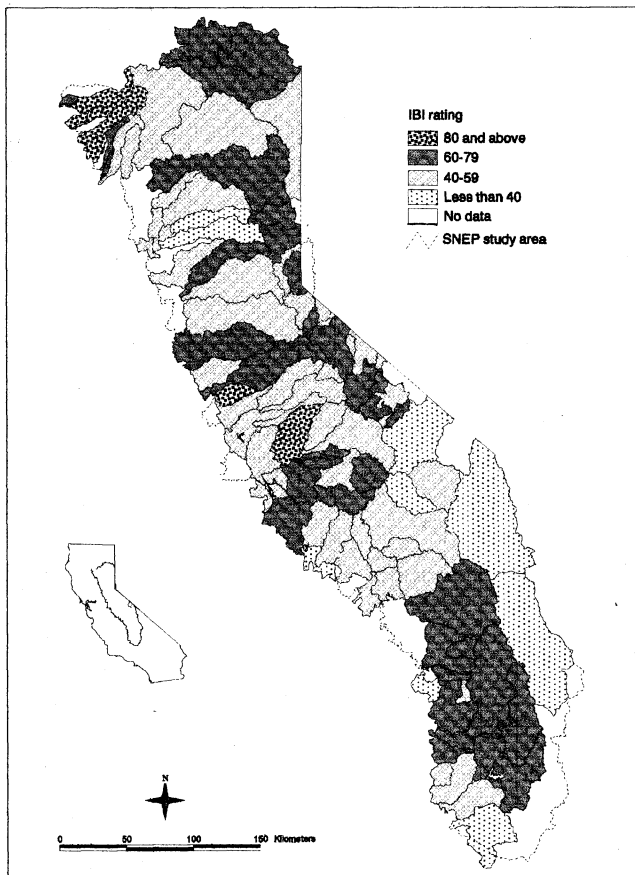


Figure 2. The W-IBI ratings for Sierra Nevada watersheds; the higher the number the better the watershed condition. Identity of the watersheds can be found in Moyle and Randall (1996).

present distribution and abundance in Yoshiyama et al. (1996). This metric was not used for watersheds in which anadromous fishes were not native. A watershed scored 1 if the anadromous fishes were now absent or extremely rare, 3 if the anadromous fishes were present mainly below dams and/or were much less abundant than formerly, and 5 if they were present throughout their original range in the watershed. Most anadromous fish scores were low.

TROUT

Rainbow trout (including golden trout) and cutthroat trout are the only trout species native to the Sierra Nevada. Historically, they lived in streams at elevations below 1600 m, except for a few high-elevation sites in the eastern Sierras and in the upper Kern River basin. A large region at high elevation was fishless until trout were introduced there by Euro-Americans in the nineteenth and twentieth centuries (Fig. 2). In addition, other species and subspecies of trout were introduced that are not native to California. Because trout are now

the dominant predators in the streams and lakes into which they were introduced, their introduction has caused the loss of native amphibians and invertebrates in lakes (Stoddard 1987; Bradford et al. 1993; Knapp 1996) and probably streams. This makes them a form of pollution difficult to eliminate. We scored this metric based on information sources similar to those used for the native fish metrics and on our map of fishless region (Fig. 2). This map was developed using information on the location of natural barriers to upstream movement of fish, the extent of Pleistocene glaciation, and historic records of trout stocking (Moyle et al. 1996). A score of 1 indicated that the range of trout in the watershed had been greatly expanded through introductions and was typically a mixture of native (to lower elevations) and exotic species. Alternately, a score of 1 could be awarded to a watershed in which trout populations had been greatly depleted as the result of environmental degradation. A score of 3 indicated that the range of trout had been somewhat expanded, usually just above barriers in tributary streams, or that the range of trout was about the same but the native populations were reduced and exotic trout were present. A 5 was given only to watersheds in which the trout present were mainly native species in their native range.

STREAM FISH ABUNDANCE

In the Sierra Nevada, high overall abundance of stream fish is a good indication of high-quality water flowing through complex aquatic and riparian habitats, whether or not the fish are native to the watershed. Dams, diversions, and other alterations of streams tend to reduce the total biomass and abundance of fish, including those of nonnative species. Abundances of fish were scored relative to presumed historic or potential levels using the same sources of information as in the native fish and anadromous fish metrics. A watershed scored 1 if fish overall appeared to be at substantially lower abundance than they presumably had been historically. This was an easy call in many streams from which salmon and steelhead had been excluded because such fish had not only been abundant by themselves but had also provided a source of food and energy for resident fishes. A watershed could also score 1 if fish were widespread and abundant in waters that were originally fishless. For a score of 3, a watershed had fish abundances that were perceived to be lower overall than historic levels but not dramatically so. For a score of 5, fish abundances were about the same or higher than historic levels. In practice, scores of 1 and 5 were easy to assign to watersheds; most others were assigned 3.

Once scores had been assigned and added, they were standardized by the following formula: total points/number of metrics \times 20, giving a possible range of IBI values of 20–100. The higher the IBI value, the better

condition of the watershed. For mapping purposes (Fig. 1), we divided the IBI values into quartiles as follows: 80–100, watershed in very good to excellent condition in terms of its aquatic biota; 60–79, watershed in good condition; 40–59, watershed in fair condition; and 20–39, watershed in poor condition.

Watershed Variables

Eight broad-scale variables for each watershed were examined in relation to W-IBI scores in order to determine the degree to which human disturbance was associated with low or high scores. Variables were chosen that measure extent of water development (dams, diversions, reservoirs), extent of human use of the watershed (measures of density of roads), and extent of trout introductions into fishless areas. It was assumed that these variables would be at least a partial measure of the effects of more-specific factors (e.g., extent of logging, grazing, and human populations) for which information was incomplete or hard to obtain. Each variable was standardized based on a geographic information system (GIS) analysis of square landscape units (pixels), each 1 ha (10,000 m² or 2.47 acres) in area: (1) dams, percentage of hectares in each watershed containing a dam of any size; (2) reservoirs, total capacity of reservoirs in the watershed, in acre feet; (3) diversions, percentage of hectares in each watershed containing a water diversion of any size (based on water rights filings, so includes small diversions that may not be active); (4) roads, percentage of hectares containing at least one road of any type, with roads being used as a measure of human disturbance of the landscape (regarded as being particularly important as a measure of urbanization, high-impact logging, and mining); (5) roads and streams, percentage of hectares containing both a road and a stream, based on the assumption that the close proximity of a road to a stream was likely to be associated with negative impacts, from siltation to instream mining to fishing, regardless of total road density in the watershed; (6) roadless area, percentage of watershed that consists of pieces at least 1000 ha in area and at least 0.2 km from a road; (7) fishless area, percentage of watershed presumably without fish historically, based on the map of Sierra Nevada fishless areas developed by Moyle et al. (1996) (Fig. 2); and (8) mean elevation, average elevation of hectares within the watershed.

The complete data set developed is available in Moyle and Randall (1996). The data were analyzed by principal components analysis. The purpose of the analysis was to determine the degree to which each of the eight variables, or combination of them, seemed to influence W-IBI scores.

Results

The W-IBI scores indicated that 7 of the 100 watersheds had aquatic communities in excellent condition (W-IBI

values of 80–100; Fig. 1). Another 36 had aquatic communities in good condition (values of 60–79), whereas 48 had aquatic communities in fair condition (values of 40–59) and 9 had aquatic communities in poor condition (values of 20–39). Of the 7 watersheds with the highest scores, 3 stand out with scores greater than 90: Deer Creek and Mill Creek (Tehama County) and the Clavey River (Tuolumne County). These watersheds contain intact native fish and amphibian faunas, and the biotic communities are still governed largely by natural processes. Deer and Mill Creeks are unusual in that they both support remnant runs of spring-run chinook salmon (Yoshiyama et al. 1996). There are three clusters of watersheds with high (>70) W-IBI scores: (1) the Deer-Mill-Antelope Creek and associated small watersheds in Tehama County, (2) the North Fork Calaveras, Clavey, and South Fork Tuolumne rivers in the western central Sierra Nevada, and (3) the upper Kings River and Kern River watersheds in the southern part of the range. Streams in the Tehama cluster flow through rugged volcanic terrain with low accessibility; the streams are also too small to make large dams viable. The western central cluster consists of medium-sized tributaries to larger, highly developed rivers that have managed to maintain much of their native fish fauna and that do not extend far into the original fishless region. The upper Kings and Kern watersheds are high-elevation watersheds with steep terrain and low accessibility. Most of their area is either in national parks or wilderness areas. In addition, most of the upper Kern River watershed was not glaciated, so trout were native to high-elevation areas. All of the high-scoring watersheds have been altered by human activity—especially fish introductions—but less so than other watersheds in the Sierra Nevada, as indicated by their moderate scores for variables related to diversions and roads. None contain large dams, however, so the natural hydrologic regimes are still intact.

Watersheds that received low W-IBI scores are (1) low-to middle-elevation drainages that have been dammed and diverted and so tend to be dominated by introduced fishes and frogs and/or to have greatly diminished native fish and frog populations; (2) high-elevation watersheds that have lost most of their frogs and that are dominated by nonnative trout; or (3) small, low-elevation watersheds that have been highly altered by human activity (urbanization, agriculture, mining, etc.), as indicated by high values for variables related to dams, diversions, and roads.

Simple correlation analysis indicated that the W-IBI score overall was negatively correlated ($p < 0.05$) with the percentage of hectares containing dams, reservoir capacity, the percentage of hectares containing roads associated with streams, and the percentage of each watershed that was historically fishless. This is not surprising, given that a low W-IBI score at high elevations would be strongly influenced by the presence of trout in naturally fishless areas, whereas a low score at low elevations

Table 1. Factors created by the principal components analysis of variables related to the biotic integrity of Sierra Nevada watersheds.

<i>Variable</i>	<i>Factor 1</i>	<i>Factor 2</i>
Watershed index of biotic integrity	-0.2242	-0.6065
Hectares containing dams (%)	0.4245	0.5541
Reservoir capacity	0.2841	0.5414
Hectares containing diversions (%)	0.5876	-0.2625
Hectares containing one or more roads (%)	0.8606	0.1116
Hectares containing a road and a stream (%)	0.8598	0.1644
Roadless watersheds (%)	-0.8997	0.0293
Watershed historically fishless (%)	-0.5394	0.5541
Mean elevation	-0.7340	0.3865
Eigenvalue	3.7754	1.5434
Variance (%)	42	17

would be related to the presence of major dams or road systems, inferring extensive development of both terrestrial and aquatic systems. This dichotomy is reflected in the results of the principal components analysis, which produced two factors with eigenvalues greater than 1.00 (Table 1). Factor 1, explaining 42% of the variance, had only a moderate negative loading on the W-IBI score but was strongly positively loaded on the two road variables and strongly negatively loaded on mean elevation and the percentage of the watershed that was historically fishless. In factor 2, explaining 17% of the variance, the W-IBI score had a high negative loading, whereas the percentage of hectares containing dams, reservoir capacity, and the percentage of the watershed that was historically fishless had high positive loadings.

Discussion and Conclusions

All aquatic ecosystems in the Sierra Nevada have lost biotic integrity to a greater or lesser degree. More than half (58%) of the watersheds, however, have been rated as having their native aquatic biota in poor to fair condition. Although we have no independent confirmation of the ratings of individual watersheds, the ratings all appear to be reasonable evaluations of the watersheds because watersheds with high scores have mostly achieved special recognition of their status (e.g., wild and scenic river designation), whereas watersheds with low scores (<50) are all in regions that have been heavily developed for hydraulic mining, agriculture, or hydropower, or a combination of the three factors. What is important about the ratings is simply the demonstration that so many watersheds have largely lost their native fish and frogs and that these watersheds are present throughout the Sierra Nevada.

Many of the processes that have contributed to the loss of biotic integrity have slowed down (e.g., trout stocking, dam construction), and a number of waters are receiving special protection in national parks as wild

and scenic rivers or through other actions such as coordinated resource management programs. There are still a few watersheds that are in remarkably good condition and many others that retain a good share of their original aquatic biota. There is no evidence to suggest, however, that the overall trend in loss of biotic integrity that the waters of the Sierra Nevada have experienced over the past 150 years has been reversed. There is every reason to suspect that the loss is continuing as new environmental problems related to human population growth are substituted for the old problems related to heavy exploitation of the landscape. In addition, exploitation of natural resources (e.g., grazing, logging, mining) continues, even if at reduced levels compared to those of 25 or 50 years ago. Thus, major efforts will be required even to maintain a good representation of the aquatic biodiversity that remains today. We recommend that this effort be focused on watershed management and that the limited resources available for conservation be focused on developing a system of protected watersheds that have both high biotic integrity and represent the range of aquatic environments in the Sierra Nevada. Moyle (1996) presents such a plan, based in part on the analysis in this paper. In degraded watersheds in which there is intense public interest (e.g., South Yuba River), rehabilitation of watersheds is highly desirable, although complete rehabilitation ultimately requires restoration of the natural flow regime, restrictions on the use of private land for mining and development, removal of dams and diversions, and re-introduction of missing species.

A watershed-based management plan for the Sierra Nevada will have to take into account the major factors affecting aquatic biodiversity. The W-IBI ratings indicate that major dams at low to middle elevations and the introduction of fish at high elevations have had the greatest effects on lowering biotic integrity. These two factors are so dominant that they tend to obscure the effects of watershed degradation, as reflected in the variables related to the abundance of roads. For example, the historically fishless areas are also mostly wilderness areas and national parks today, and so have low numbers of roads, yet the presence of introduced fish and the frequent scarcity of ranid frogs greatly reduces the biotic integrity of the waters within these areas. In general, the watersheds with the highest W-IBI scores are at intermediate elevations, are without major dams, and have low to intermediate scores for variables related to human disturbance (roads, diversions).

The importance of dams and introduced species in reducing biotic integrity does not mean that other factors are not important, especially for smaller watersheds or for individual situations. Streams that are subject to high levels of sedimentation from numerous or poorly constructed roads, from mining, from grazing, or from logging on steep hillsides will have reduced diversity of aquatic organisms, as will streams that have had their

channels heavily modified for flood control or other purposes (e.g., Moyle 1976b). Streams heavily polluted by acidic water leaching out of abandoned mines exhibit very low diversity of organisms. Most of these factors are likely to be localized in their effects and reversible, however, often just by cessation of the problem-causing activity, provided there are nearby sources of missing species. The native fish populations in particular have a high capacity to recover from decimation (Moyle et al. 1983). For example, many small tributaries to the South Yuba River were devastated by hydraulic mining in the nineteenth century yet today show some recovery of their native fish and amphibian faunas (Gard 1994; P.J.R., unpublished data). A few species of fish still missing from the South Yuba fauna appear to have been unable to reinvade because the combination of dams and introduced predators has made the movement of native fish through the main river difficult or impossible (Gard 1994).

Although the analysis we present applies mainly to large-scale patterns on the landscape, we think it has considerable potential to be applied to other regions as well because (1) it does provide a vision for the entire region, (2) it promotes recognition that declines in biotic integrity have multiple causes, both local and regional in origin, (3) it provides a good place to start for more detailed analyses, and (4) it provides a basis for making watersheds a basic unit of conservation. The fact that *all* aquatic ecosystems in the Sierra Nevada have been altered by human activity in the past 150 years is not widely recognized because so much of the range is protected in national parks and wilderness areas. Introduced trout are regarded by most people as a natural part of the high mountain environment; only recently has it been recognized how much they have altered alpine ecosystems (Knapp 1996). Likewise, the extent to which dams and diversions have altered natural aquatic systems is not widely appreciated because altered streams and lakes often still support large recreational fisheries (Moyle et al. 1996). Because the Sierra Nevada is divided among numerous jurisdictional boundaries, the cumulative, range-wide effects of an economy dependent on exploitation of local resources—through recreation, grazing, mining, logging, water development, and so forth—is rarely recognized. This analysis, as well as other analyses conducted as part of the Sierra Nevada Ecosystem Project, can provide this recognition, indicating that range-wide solutions to the problems are needed. An analysis of this type can also provide recognition that some problems are still increasing in severity and have wide-scale impacts. For example, a major factor lowering many of the scores was the scarcity or absence of native frogs from watersheds, with much of the decline in frogs taking place in the past 25 years. The causes of frog declines (e.g., introduced diseases, increase in ultraviolet radiation) may be unique to amphibians, with little impact on the rest of the

native biota (e.g., Drost & Fellers 1996). But the sudden and almost complete disappearance of foothill yellow-legged frogs from mid-elevation habitats in the southwestern quarter of the range and not in the northwestern quarter implies that airborne toxic compounds of local origin (e.g., agricultural chemicals from the San Joaquin Valley) are responsible (Cahill et al. 1996). There is no guarantee that the effects of such chemicals will be confined to frogs in the future, and the devastation of native aquatic faunas characteristic of the valley floor (Moyle 1976a; Fisher & Shaffer 1996) may become characteristic of higher elevations as well.

A serious problem with an analysis on the scale of this one is that it overlooks important smaller watersheds or aquatic systems. For example, the North Fork of the Kings River received a mediocre W-IBI score (52) because of its shortage of native fish and frogs (the result of hydroelectric development and of being highly disturbed by logging and recreational use) and because its high-elevation waters are filled with nonnative trout. But within this drainage is Rancheria Creek, a relatively inaccessible watershed that is one of the most undisturbed in the Sierra Nevada (E. Beckwitt, personal communication). This indicates an urgent need to conduct detailed surveys within all watersheds to identify special, unusual, or relatively undisturbed aquatic systems at a smaller scale, especially in watersheds with low ratings that are undergoing rapid change through land and water development. Such systems would be prime candidates for special protection as preserves (Moyle & Yoshiyama 1994).

In conclusion, there is little reason to doubt that the aquatic biota of the Sierra Nevada has been drastically altered by human activity on a broad scale and that its decline is continuing. This trend is likely to be reversed only by conservation actions taken at the watershed scale throughout the range, including (1) making a representative set of watersheds with aquatic biodiversity the first goal of management, (2) identifying smaller special areas to be protected as preserves, and (3) supporting watershed-oriented management activities throughout the Sierra Nevada (Moyle 1996). Such a program could be funded through a tax on the range's major export, water.

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