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35

Status of Aquatic Invertebrates

ABSTRACT

The aquatic invertebrate fauna of the Sierra Nevada is diverse and extensive, with many endemic species throughout the range. Aquatic systems differ widely in the Sierra because of such natural factors as elevation, climate patterns, geology, substrate type, water source, water volume, slope, exposure, and riparian vegetation. These differences are reflected in the aquatic invertebrate fauna. Small, isolated aquatic habitats such as springs, seeps, peatlands, and small permanent and temporary streams have a high probability of containing rare or endemic invertebrates. Aquatic invertebrates are a major source of food for birds, mammals, amphibians, reptiles, fish, and other invertebrates in both aquatic and terrestrial habitats. Changes in a food source of such importance as aquatic invertebrates can have repercussions in many parts of the food web. The life cycles of aquatic invertebrates are intricately connected to land as well as water, and the majority of aquatic invertebrates spend part of their life cycle in terrestrial habitats. Aquatic invertebrates are affected by human-caused activities on land as well as activities in the water. Land and water uses and impacts are reflected in species assemblages in streams and lakes. Changes in aquatic invertebrate assemblages have been used for many decades to monitor impacts on land and in water. However, the level of detail of most monitoring is not sufficient to track species losses in aquatic invertebrates. Aquatic invertebrates have not been inventoried or well-studied at the species level in most of the Sierra. Aquatic invertebrates are rarely considered or evaluated in environmental impact assessments in the Sierra. Major changes have occurred in aquatic and terrestrial habitats in the Sierra over the last 200 years: we must logically assume that corresponding changes have occurred in aquatic invertebrate assemblages.

INTRODUCTION

To assess the status of aquatic invertebrates in the Sierra Nevada, we must first consider the status of aquatic habitats. Aquatic invertebrates have complicated life cycles that are inextricably connected to both aquatic and terrestrial environments (Erman 1984b). The impacts of human use of land and water are reflected in species assemblages in streams and lakes. As Gregory and colleagues (1987) noted, "The landscapes and biotic communities of terrestrial and aquatic ecosystems are intricately linked, and effective management must acknowledge and incorporate such complexity." Changes in aquatic invertebrate assemblages are measurable and have been used as a monitoring tool for more than eighty years (e.g. Cairns and Pratt 1993); thus, we know that invertebrate assemblages change with habitat changes. Major changes have occurred in aquatic habitats in the Sierra Nevada over the last 200 years (Beesley 1996; Kattelmann 1996; Kondolf et al. 1996; Mount 1995). We must logically assume that, as land and water are altered in the Sierra Nevada, aquatic invertebrate assemblages are changing; populations (e.g., Taylor 1981) and perhaps species are being lost. But most of these changes are occurring at unknown and undocumented rates.

In California, we do not have inventory data on aquatic invertebrates from 200 years ago. But neither do we have adequate inventory data on aquatic invertebrates at present. We have surveys of specific invertebrate groups in a few geographic areas of the Sierra, but a surprisingly small amount of survey information at the species level exists. There are not adequate systematic invertebrate inventories or surveys for even the national parks (Stohlgren and Quinn 1992). On the other hand, the responses of aquatic invertebrate assemblages to land and water alterations are well-known and have

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been studied for decades in many parts of the world and, to some extent, in California. Therefore, we can predict generally how invertebrate assemblages will change in response to such environmental impacts as logging, grazing, mining, water development, construction, human settlement, and the introduction of exotic species. Habitat loss and degradation and the spread of "exotic" (non-native or nonindigenous) species are the greatest threats to biodiversity in running-water systems (Allan and Flecker 1993; Wilcove and Bean 1994). The extent of change in California river systems has recently been documented (California State Lands Commission 1993; Mount 1995). California may be unsurpassed for the extensive geographic scale and short time scale on which these basic changes have occurred.

Questions about invertebrate status in Sierra Nevada aquatic habitats are as follows:

- Are species disappearing?
- Are species assemblages changing or becoming simplified in response to changes in habitats?
- What is causing these changes?
- What can be done to reverse these changes?

Perhaps a fifth question we should be asking is

- Why have aquatic invertebrates been so little studied and so little considered in management in the Sierra Nevada and in California, in general?

This assessment can only begin to answer these questions.

Many aquatic invertebrates have specific and narrow habitat requirements and are restricted, therefore, to places that vary little from year to year. Others are generalists and can survive over a wide range of habitat types (Thorp and Covich 1991). The differences between these two groups and all the gradations between them are crucial to our understanding of what has been happening to aquatic invertebrate species and assemblages of species in the Sierra Nevada over the past 200 years, especially since the gold rush, when major alterations of aquatic systems began in the Sierra.

A knowledge of aquatic invertebrates at the species level is essential to assessing the status of biodiversity in the Sierra. Monitoring of invertebrates at a higher taxonomic level (genus, family, order) can be useful in indicating changes in invertebrate assemblages in response to some impact if proper controls are established, but such monitoring usually cannot determine loss of species. The term "species" has the same meaning for aquatic invertebrates as it has for any other group of living things; aquatic invertebrate species are not interchangeable. Just as the common pigeon (rock dove; Columbidae: Columba livia) is not the same bird as the band-tailed pigeon (Columbidae: Columba fasciata), nor a white fir the same as a giant sequoia, neither is one species (or genus, family, or order) of aquatic invertebrate the same as another. Each species has different habitat requirements and different tolerances to environmental variables.

Endemic species of aquatic invertebrates in the Sierra Nevada (and in mountains in general) are often isolated at all elevations in small first- and second-order stream systems and can be limited in distribution to such habitats as springs, peatlands, and small headwater streams (Erman and Erman 1975; Hampton 1988; Stewart and Stark 1988; Erman and Erman 1990; Wiggins 1990; Erman and Nagano 1992; Hershler 1994). Some groups of aquatic invertebrates (e.g., some families of stoneflies, caddisflies, flatworms, and snails) exhibit high species endemism and great diversity in the Sierra Nevada.

Fish assemblages are not indicators or surrogates for aquatic invertebrate communities in much of the Sierra. Fish communities are not diverse in the Sierra; game fish have been introduced and moved throughout the range by humans, and some (e.g., rainbow, brown, and golden trout) are more tolerant of degraded habitats and/or a broad spectrum of conditions than are many invertebrate species and invertebrate assemblages. Historic distributions of fish were very different from current distributions, and much of the Sierra was originally fishless (see Knapp 1996; Moyle et al. 1996). Further, many small aquatic habitats rich in endemic invertebrates are lacking fish species.

Aquatic invertebrates are an important source of food for birds, mammals, amphibians, reptiles, fish, and other invertebrates. Changes in terrestrial and aquatic habitats lead to changes in invertebrate assemblages, which in turn increase, decrease, or change food supplies for other animals. As impacts occur in a stream, species (or taxa) richness (number of species) decreases but the population size of some species may increase. Further, large-sized species are usually replaced by small species (e.g., Wallace and Gurtz 1986). Conversely, when the stream condition improves, larger invertebrate species replace small species (Grubaugh and Wallace 1995). Such changes can have critical impacts on species that depend on invertebrates for a food supply.

Aquatic systems differ widely throughout the Sierra because of such natural factors as elevation, climate patterns, geology, substrate type, water source, water volume, slope, exposure, and riparian vegetation. For these reasons it is not possible to describe a typical Sierran stream, lake, spring, peatland, and so on, or a typical invertebrate assemblage. The natural variability among aquatic habitats must be understood when the effects on invertebrates of anthropogenic disturbance are studied.

The waters of the Sierra are the responsibility of many federal, state, and local agencies and are subject, through these agencies, to many laws and regulations. How these agencies work together and how they apply and enforce these laws determine the fate of the aquatic biota. Making connections among the aquatic biota, aquatic habitats, and institutional responsibility and performance is necessary to understand the present state of and future possibilities for Sierra waters.

PROCEDURES AND METHODS

To assess the extent of aquatic invertebrate work in the Sierra Nevada, we searched several standard library databases, using an extensive list of invertebrate names and aquatic habitat keywords. This method, while not complete, gave a reasonable indication of research on aquatic invertebrates over approximately the last twenty years (the general period covered by the databases). Key researchers were contacted to fill in some gaps in the list of studies. These contacts revealed that several papers had been missed in the databases, but also that the technique had given a fairly thorough indication of the topics being studied and of primary researchers or groups of researchers doing the work. For purposes of analysis, studies were grouped into a few general categories by geographical area or type of study. These groups were (1) taxonomic studies, (2) impact studies, (3) geographic surveys of certain taxonomic groups, (4) behavioral studies, (5) studies pf Mono Lake, (6) studies of Lake Tahoe, (7) other lake studies, and (8) studies on mosquitoes.

With such arbitrary groupings, there was much overlap. For example, many of the studies of Lake Tahoe could be considered impact studies or behavioral studies. But the groupings were made to provide an understanding of distinct aquatic systems or problems and to discover the studies' relevance (or lack of it) to the SNEP objective of assessing status. Much money has been spent on mosquito research and there were many papers on this group of organisms, but mosquitoes were not evaluated for this chapter. The reasons for this will be discussed later.

In addition to the general search of databases, we contacted agencies through a letter asking for information and made individual contacts with people known to have specific information on invertebrate work. This step revealed unpublished, nonrefereed reports and studies for which data sheets and notebooks, but no reports, existed.

A third step was to contact experts from North America known to be working on certain groups of invertebrates in an attempt to compile up-to-date species lists for the Sierra and to get some idea of the percentage of endemism among Sierra aquatic invertebrates. Most of these efforts are ongoing and incomplete. Recent published information for some groups (e.g., stoneflies, caddisflies, alderflies, dobsonflies, snails, and clams) was sufficient for estimates. Large gaps in our understanding and knowledge of aquatic invertebrates in California and in the Sierra are evident and will be discussed in a later section.

A fourth source of available information is museum collections. However, the short time allowed for this project did not permit us to explore these. Such collections as the California Academy of Sciences; the Bohart Entomology Museum at University of California, Davis; the Los Angeles County Museum; and the University of California, Berkeley, entomology museum have material from the Sierra, as do many other museums in North America (e.g., the Smithsonian and the Royal Ontario Museum in Toronto). Museum material is known and up-to-date for invertebrate groups being actively investigated by experts. But much other material has not been studied, and information is undoubtedly contained in these sources. To have meaning, this material requires examination by experts who are currently studying systematics in their respective fields. Taxonomy has changed rapidly and significantly in many invertebrate groups over the last twenty-five years. Hence, each specimen must be examined to determine its classification.

This chapter deals largely with aquatic macroinvertebrates (those that can be seen with the naked eye), not with the microinvertebrates (those that require a microscope to be seen). Such microinvertebrates as protozoans, tardigrades, and rotifers, for example, have not been assessed. The emphasis in this chapter is on running-water habitats. Some examples, however, are from standing-water habitats.

HISTORIC CONDITIONS AND AGENTS OF CHANGE

By describing conditions that existed in the Sierra Nevada prior to the immigration of Europeans and Asians, that is, conditions of 200 or 300 years ago, we can understand better what has happened to aquatic habitats and what the implications of those changes are for aquatic invertebrates. The numeric assessment of change to aquatic habitats (the numbers of dams, diversions, roads, grazing allotments, etc.) is described elsewhere (for example, see Kattelmann 1996, Menke et al. 1996, and Kondolf et al. 1996); therefore, this section gives a general description only, for the purpose of demonstrating habitat under which aquatic invertebrate species and species assemblages evolved in the Sierra Nevada over thousands of years and how that habitat has changed. It is not a complete listing of all of the changes and impacts that have occurred in Sierra aquatic invertebrate habitats.

Two hundred years ago Sierra Nevada streams were continuous running-water systems: there were no dams, reservoirs, water diversions, or interbasin transfers of water. There is no, or almost no, similarity between invertebrate species assemblages in running water and those in standing water. The major taxa of many invertebrate groups are found in both general habitat types, and in gradations between them, but the species that live in these two habitats are usually different. For example, true flies, in the order Diptera (a major insect taxon) are found in both reservoirs and in rapidly flowing water, but the species, and in many cases the genera and families, are different in the two habitat types. To continue this example, a family of true flies called the net-winged midges, Blephariceridae, is found exclusively in rushing mountain streams. It has suction-cup-like attachments on the underside of its larval body and lives only in the strongest currents. Widespread construction of dams throughout the mountainous areas of California has probably changed the distribution and possibly decreased the number of species of this family of flies.

In general, burrowing Chironomidae larvae (another type of midge fly in the order Diptera) and oligochaetes (aquatic segmented worms) predominate in habitats where sediments accumulate (Johnson et al. 1993), and their numbers rise where streams have been converted to reservoirs. Stoneflies (Plecoptera), found primarily in running water, are eliminated in reservoirs (Stewart and Stark 1988).

To illustrate the scope of change, figure 35.1 shows the locations of dams that are more than 7.6 m (25 ft) high or that have a capacity greater than 61,674 m3 (50 acre-ft). Smaller dams and water diversions exist on many other small Sierra Nevada streams but are not shown in this figure. Prior to the construction of reservoirs, natural hydrologic cycles existed on all streams and rivers. Water was high in the winter and spring and low in the summer and fall. Invertebrate life cycles evolved over thousands of years in response to such hydrologic cycles. Invertebrate biomass in the water was highest during the high water period and lowest in the summer and fall. Aquatic insects are the largest component of the aquatic invertebrate community, and most of them emerge as terrestrial adults in summer and fall in the Sierra Nevada, with fewer species emerging in spring and a small minority emerging in the winter (e.g., Erman 1989). Thus, invertebrate biomass is low when the water is low because many insects are in the terrestrial stage or are in the egg or small larval stage.

Invertebrates can accommodate the natural rise and fall of floodwater by moving up with the water and outside the stream banks, by burrowing into the substrate, or by taking refuge in root wads and debris along stream edges. They return to the stream channel as the water recedes. Natural floods perform the function of flushing sediment from the stream system, which, in turn, increases pore spaces within the stream-bottom substrate and provides surface area for invertebrates to inhabit.

The suddenly fluctuating water caused by some dams and water diversions has a different impact on invertebrate populations than does a natural flood. Invertebrates are stranded as water volume is lowered suddenly and stream channels dry up. Also, invertebrates drift downstream when water is rapidly lowered or raised (Minshall and Winger 1968; Bovee 1985). Year-round constant flow, a condition found in some artificially managed streams, is also abnormal to invertebrate communities of the Sierra Nevada. Under constant flow, sediment is not flushed from streams, and other poorly understood triggers to life cycle changes and in-stream migrations may not be present (Reiser et al. 1989).

Sediment from mining, logging, cattle grazing, roads, and construction had not entered Sierran streams 200 years ago. Natural sources of sediment, such as landslides from heavy rains and fires, were present, of course, prior to our recent history, as they are today. We can assume, therefore, that the quantity of sediment entering the aquatic systems of the Sierra today is far greater than it was. Much of this sediment is trapped behind dams at present (where it causes problems in water storage operations) (Kattelmann 1996) and is thereby removed from the stream system below dams. One example is the Mokelumne River watershed basin, where erosion rates estimated over the last twenty-five years are more than eight times higher than they were in 1944 (Robert C. Nuzum, Director of Natural Resources, East Bay Municipal Utility District, letter to Don C. Erman, September 25, 1995). The primary land use in the basin is timber harvesting (consisting of 98.5% of the land base).

The effects of sediment on aquatic macroinvertebrates have been amply demonstrated and known for many years (e. g., Cordone and Kelley 1961; Buscemi 1966; Chutter 1969; Brusven and Prather 1974; Luedtke et al. 1976; Waters 1995). In streams, sediment accumulation depletes available habitat for invertebrates, as pore spaces in the rocky substrate are filled with sand and silt. Over time, continued sedimentation can create a cemented stream bottom with no substrate pore spaces available for invertebrate colonization. Only a few highly tolerant invertebrate species will persist in these conditions. The gold mining areas contain examples of sediment accumulation that are even more dramatic. There, certain streams have become so filled with sediment that surface flow no longer exists. Where 200 years ago rocky-bottomed streams flowed, today sediment-filled, seasonally dry stream channels are evident many feet above the original channel (Mount 1995). A striking example of this impact is Shady Creek on Highway 49 near North Columbia. As sediment increases, species richness, density, and biomass decrease. Sediment obstructs respiration, interferes with feeding, causes loss of habitat and habitat stability, and may alter production of invertebrate food sources (Johnson et al. 1993).

In the past, streams were more shaded and were lower in temperature because there was more riparian cover. Headwater streams were deeper and narrower, in meadows and wetlands. They had rocky bottoms and were covered by either willows or alders, or by sedges and grasses. Today, small first- and second-order streams (small streams in the headwaters of river basins and also in river branches at all elevations of the Sierra) of this description are found largely in national parks. Livestock grazing has decreased or eliminated riparian vegetation, broken stream banks, widened stream bottoms, increased sediment, decreased shade, and increased water temperature (Platts 1978; California State Lands Commission 1993; Fleischner 1994; Li et al. 1994; Menke et al. 1996).

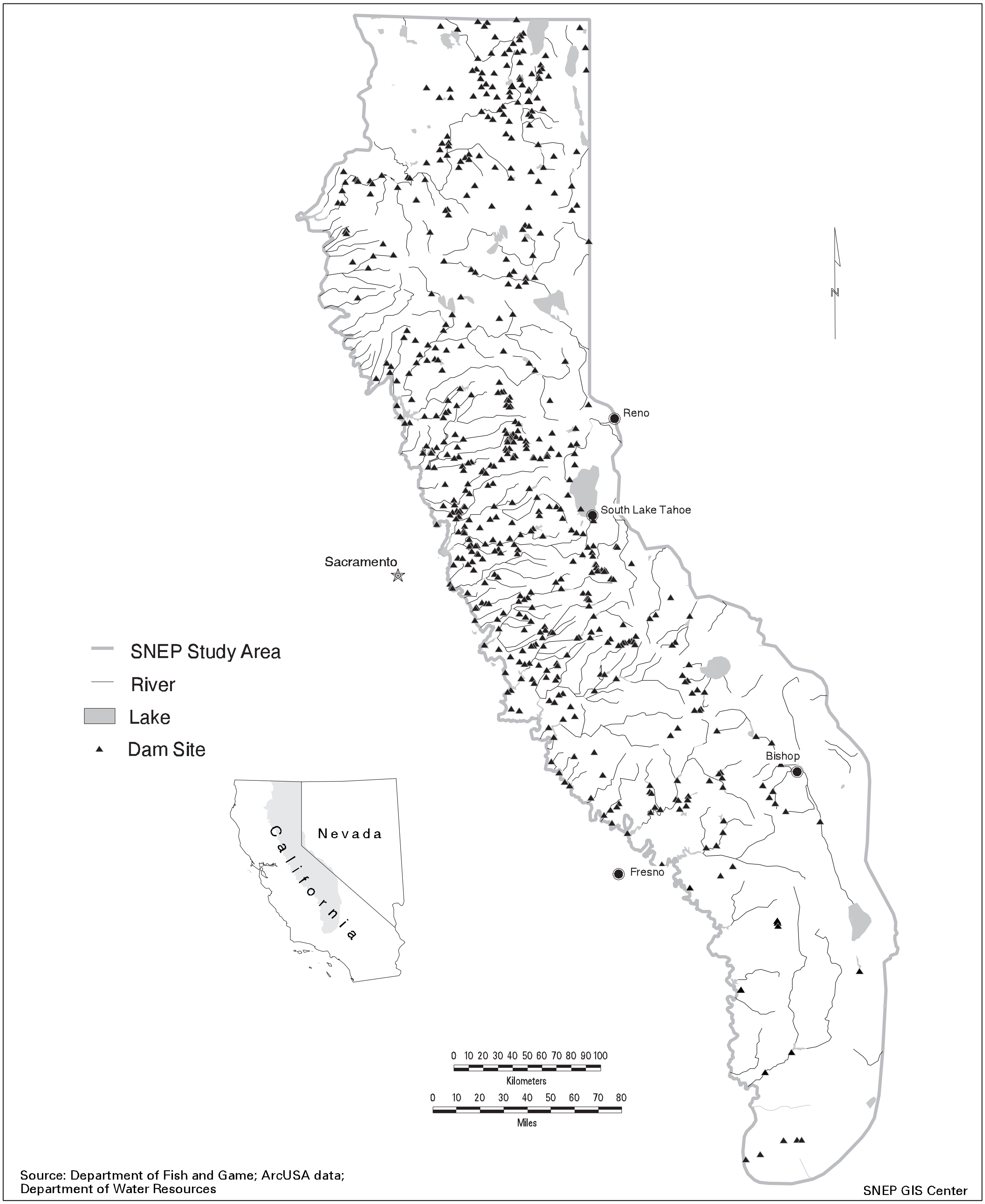

FIGURE 35.1

Dams in California that are at least 7.62 m (25 ft) high or that have a capacity greater than 61,674 m^3 (50 acre-ft) (from California State Lands Commission 1993).

Stream channels in the presettlement period meandered in areas of low gradient; they had not been straightened for logging, mining, or road building. Streams were not artificially confined to a channel. We can probably can assume that there was more wood in streams (Sedell and Luchessa 1982). Wood has been intentionally removed by state and federal agencies, including the California Conservation Corps, and by loggers and woodcutters. In addition, downed wood was retained more easily in meandering stream channels (Sedell and Maser 1994). Wood in streams serves several functions for invertebrates. It retains organic matter (leaves, sticks, and needles) that falls into the stream. It slows the water and creates pools, thereby allowing the opportunity for invertebrates to feed on organic matter, which increases the efficiency of nutrient use. Wood creates complexity of habitat by forming pools and breaking up otherwise long stream runs. And some invertebrates feed specifically on the wood or attach themselves to the wood and feed on the algae, microinvertebrates, and bacteria that grow on wood (Murphy and Meehan 1991).

Two hundred years ago, streams were not diverted from their channels into ditches or pipes. There had been no dynamiting of fish barriers, and so some stream sections had isolated populations of invertebrates. There was no heavy metal contamination of water from mining, no dredge mining in channels, no concrete, no modern building, no bridges, no riprapped banks.

Springs had intact riparian vegetation, untrampled by livestock and unlogged. Some springs must have been used by Native Americans, but they probably were not channeled. And they were not sprayed with herbicides or diverted, as they are today for a variety of reasons, some of which include game management (Bleich 1992). Nor had ground-water pumping dried springs (DeDecker 1992). The potential for loss of endemic aquatic invertebrate species from springs, due to present management and use, may be greater than from any other aquatic habitat and will be discussed later.

Fish assemblages were different in the past from those of today, and the reasons for this change have had significant implications for invertebrates. Fish had not been transported or introduced from Europe or put into high-mountain lakes (see Knapp 1996; Moyle et al. 1996). In addition, the introduction of fish into reservoirs has resulted in upstream as well as downstream changes in fish assemblages because fish move out of reservoirs (Erman 1973, 1986). Much of the upper Sierra was fishless 200 years ago (Moyle et al. 1996). The introduction of a top predator can cause many changes in invertebrate assemblages, as discussed in detail by Knapp (1996).

Intentionally introduced invertebrate species, not present 200 years ago, are also causing community changes in Sierra waters. Examples are the opossum shrimp, Mysis relicta (Richards et al. 1975, 1991) and the signal crayfish, Pascifasticus leniusculus (Flint and Goldman 1975; Elser et al. 1994). Other invertebrates likely have been introduced unintentionally with the introduction of fish and with transfers of water within and between basins.

Hundreds of miles of stream and many lakes had not been poisoned by rotenone or other piscicides 200 years ago. The scale of rotenone use in the Sierra was not determined for this chapter, but a few published examples give an indication of the extent of its use. Rotenone has been used by the California Department of Fish and Game (CDFG) in California "for more than 45 years" (CDFG 1994a, 1994b). "In the past we have routinely treated the streams in a drainage . . . before impoundment" (Hashagen 1975). In the Kern River, drainage piscicides (rotenone and antimycin) have been used several times since 1960. Present ongoing plans are to poison 37 miles of the South Fork Kern River and its tributaries between 1994 and 1996 (CDFG 1994c). Between 1952 and 1954 a total of 286 miles of stream in the Russian River drainage (the tributaries and most of the main river) were poisoned with rotenone (Johnson 1975). Though not in the Sierra, the Russian River example gives an idea of the scale of past rotenone use in California. Rotenone and antimycin reduce populations of many aquatic invertebrates when applied to a body of water (Cook and Moore 1969; Degan 1973; Stefferud 1977; Maslin et al. 1988). This fish-management technique likely has simplified invertebrate communities, especially where used repeatedly. Although Native Americans used fish poison in streams as a fishing technique, the scale was much smaller and was not extensive in the Sierra (Rostlund 1948).

Insecticides, herbicides, fertilizers, and fire retardants had not been used over large parts of the Sierra landscape 200 years ago. Their effect on aquatic invertebrates may be significant (Norris et al. 1991). The scale of use and impact is unknown.

Humans with modern conveniences had not moved into wildland areas in record numbers. Even such small inventions as electric blacklight (ultraviolet) bug zappers may have a local impact on aquatic insects. Ultraviolet lights are known insect attractants; high numbers of night-flying female caddisflies, many with egg masses attached, are attracted to them (N. A. Erman, unpublished data). Ironically, while attracting many insects, they have little, if any, effect on their target insect, the mosquito, because most female mosquitoes are not attracted to ultraviolet light, according to Turpin as quoted in Purdue University 1993.

Fire probably had no more impact on Sierra streams and riparian zones in the past than it has today, although because drought cycles play a role in fire frequency there may have been longer periods of more fire in the past (Stine 1996). The effects of fire on streams are local and individual. Examples can be seen in the Sierra today of places where fire has jumped over streams and riparian areas, whereas, in other places, fire has burned to the stream edge.

Droughts have been cyclical in the Sierra over thousands of years, and some were longer and more severe than our recent eight-year drought (Fritts and Gordon 1980; Erman and

Erman 1995; Stine 1996). Many springs and wetlands (meadows and fens or minerotrophic peatlands) must have dried out or disappeared during those periods. Evidence indicates that the past 100 years or so has been a period of high moisture (Stine 1996).

Flooding of stream channels, on the other hand, probably was not as severe 200 years ago as it is under our present land use. We can assume that with more vegetative cover and fewer perturbations on the land, especially those due to road systems (Kondolf et al. 1996), water soaked into the soil in greater amounts than it does today.

In summary, invertebrate assemblages in the past were probably richer and species diversity was probably higher; that is, there were more species and their relative abundances were more evenly distributed in many habitats than they are today. Many cumulative impacts are present in Sierra Nevada aquatic systems that were not present 200 years ago. These impacts have a combined and often synergistic effect on stream systems. It is reasonable to assume that some species have probably disappeared from small, unique, isolated habitats (spring systems, small upper watershed streams, peatlands, and perhaps, high-mountain lakes and ephemeral ponds) that have been substantially altered or eliminated.

CURRENT CONDITIONS

Aquatic Invertebrate Resource

Endemic or Unusual Species

Many endemic species of aquatic invertebrates, known nowhere else in the world, are present in the Sierra Nevada. A wealth of evolutionary, ecological, and biogeographical information is contained in Sierra aquatic invertebrates. Among the more notable examples is the stonefly Capnia lacustra, present only in Lake Tahoe (Jewett 1963), the only stonefly in the world known to be fully aquatic in the adult stage (Nelson and Baumann 1989). Another unusual stonefly, Cosumnoperla hypocrena, is known from one intermittent spring in the Cosumnes River Basin (Szczytko and Bottorff 1987). Extensive searching has failed to produce this species from any other site. Worldwide, few stoneflies are known from intermittent habitats. A caddisfly, Desmona bethula, has been studied in sites at about 1,970 m (6,500 ft) elevation, where it leaves the stream on warm summer nights as an aquatic larva to feed on terrestrial vegetation, a behavior undescribed in the world prior to its being studied in the Sierra (Erman 1981). This species, too, is known from a small number of Sierra Nevada sites. Another caddisfly, known only from small streams in the Sierra, the Siskiyous, and the Cascades, Yphria californica, is possibly the most primitive living species of the tube-case-making caddisflies in the world (Wiggins 1962; Anderson 1976). A species of brine shrimp, Artemia monica, is endemic to Mono Lake (Belk and Brtek 1995). In the Sierra Nevada the symbiotic relationship between the midge larva Cricotopus and the algae Nostoc was discovered (Brock 1960). Endemic species of flatworms (Kenk 1970, 1972; Kenk and Hampton 1982; Hampton 1988), of amphipods (Holsinger 1974), and of hydrobiid snails (Hershler and Pratt 1990; Hershler 1994) have all been found in the Sierra. These are but a few of many such examples.

The percentage of endemism in aquatic invertebrates in the Sierra is apparently much higher than in terrestrial invertebrates (Kimsey 1996; Shapiro 1996). The reason is the discrete and isolated nature of small aquatic habitats in mountainous areas. The pattern for endemic amphibians occurring in aquatic habitats is similar to that of endemic aquatic invertebrates (Jennings 1996).

Aquatic Invertebrates as a Food Source

While the foregoing examples are of unusual species that are of great evolutionary interest to scientists, they may not be understood by most people as being of value. We are rarely taught the connections between small, seemingly obscure species and the larger species with which we are all familiar (Kellert 1993). And yet, in the details of small, unknown animals lies the fate of the animal world (Wilson 1987).

For example, the brine shrimp and alkali fly of Mono Lake provide food for thousands of migrating waterfowl from North and South America (Vale 1980; Lenz et al. 1986). Decreasing fresh water and increasing salinity in Mono Lake led to decreases in the alkali fly Ephydra hians prior to restoration of inflows to the lake and was the subject of concern and study of this critical invertebrate species (Herbst 1990, 1992; Herbst and Bradley 1993).

In Lake Tahoe, introductions of exotic fishes and an exotic invertebrate, the opossum shrimp, Mysis relicta, have led to periodic decreases in and disappearances of native zooplankton, species of Bosmina and Daphnia, which in turn have caused food shortages for fish (e.g., Goldman et al. 1979; Morgan 1979, 1980; Morgan et al. 1978; Richards et al. 1975, 1991) and possibly have caused increases in algae and decreases in water clarity. This story continues and is not completely understood. Suffice it to say that Lake Tahoe is now far from being a natural biotic community, and poorly considered introductions of exotic species, both fish and invertebrates, have played a major role in some of the changes that have occurred in the lake.

Aquatic invertebrates, in general, provide food to a vast array of birds, reptiles, amphibians, mammals, fish, and other invertebrates. Aquatic insects live in an aquatic habitat for only part of their lives and are terrestrial during other life stages, where they live primarily in riparian areas (Erman 1984b). They are a food source in all life stages for invertebrate-feeding animals in aquatic and riparian areas. Adult insects constitute a substantial percentage of the arthropod biomass and numbers near streams (Jackson and Fisher 1986;

Jackson and Resh 1989). Their numbers decline but are still significant 150 m (492 ft) or more from streams (Jackson and Resh 1989). This contribution of aquatic insects to the total arthropod assemblage near water makes riparian areas rich in food. Any vertebrate that is found in wet areas in the Sierra and that is known to eat invertebrates is likely feeding on aquatic invertebrates at some time. Many of these interrelationships have not been studied and are unknown in their specific details (but see, for example, Busby and Sealy 1979) but nevertheless are understood generally (Zeiner et al. 1988, 1990a, 1990b). For example, many of the bat species present in the Sierra forage over water for insects (Ron Cole, University of California, Davis, Department of Wildlife, Fish, and Conservation Biology, communication with the author, 1995; Zeiner et al. 1996). The water shrew eats aquatic insects, as may other shrews found in riparian areas (such as the vagrant shrew and the dusky shrew). Some part of the diet of the western jumping mouse, confined to wet areas, is likely aquatic insects, as are portions of the diets of the river otter, gray and red fox, mink, raccoon, marten, and western spotted skunk (Zeiner et al. 1990b).

A large number of bird species are dependent on aquatic invertebrates, either during all life stages (e.g. the American dipper, pied-billed grebe, and eared grebe); or during critical stages of breeding or the early life of the young (e.g., the gadwall, wood duck, tundra swan, American wigeon, belted kingfisher, red-winged blackbird, and yellow-headed blackbird); or during parts of the year when other food is unavailable. The list of birds that feed on invertebrates in and over wetlands, lakes, or streams is extensive (e.g., the hooded merganser, common merganser, spotted sandpiper, Forster's tern, black tern, tree swallow, violet-green swallow, bank swallow, barn swallow, willow flycatcher, black phoebe, Swainson's thrush, and yellow warbler). The few examples given here show the diversity of bird life in the Sierra and the northeastern plateau of California that depends on this food source (Zeiner et al. 1990a).

Several threatened amphibian species in the Sierra are highly dependent on aquatic invertebrates during the adult stage of their lives; these include the red-legged frog, foothill yellow-legged frog, mountain yellow-legged frog, and spotted frog (not in the Sierra but in Modoc County). Further, locally distributed salamanders that are present in springs and seeps—the Inyo Mountains salamander, and Mount Lyell salamander—likely feed on aquatic invertebrates. Also, the long-toed salamander, rough-skinned newt, California newt, and Yosemite toad, and the western pond turtle, a reptile, are all known to eat aquatic invertebrates (Zeiner et al. 1988). But this list is far from complete, and interested readers are referred to the three-volume work California's Wildlife (Zeiner et al. 1988, 1990a, 1990b) for specific details and references on Sierran vertebrate species.

Of course, many fish also depend on aquatic invertebrates, as do all animals that feed on those fish (e.g., the great blue heron, belted kingfisher, bald eagle, marten, mink, and river otter).

When a food source of such importance and magnitude as aquatic invertebrates is changed or extinguished in an area, even temporarily, it can have repercussions in many parts of the food web.

State of Knowledge of Aquatic Invertebrates

California has never undertaken the task of systematically and thoroughly surveying the invertebrates of its aquatic habitats, and in this regard, we lag behind the eastern United States, Europe, and much of Canada. Lack of expertise in California universities and state and federal resource agencies is a reason for this paucity of inventory data on aquatic invertebrates (see also Kimsey 1996). A shortage of aquatic invertebrate taxonomists and systematists worldwide is an obstacle to developing an understanding of issues of changing biodiversity and the impacts of environmental degradation (Disney 1989; Ehrenfeld 1989; Wiggins 1990; Erman 1992a).

Obsolete taxonomic keys and species lists are a problem for students of California aquatic invertebrates. When, Aquatic Insects of California was first published by Usinger in 1956 (it was reissued in 1963 and 1968) (Usinger 1956), it was considered a landmark work for a state and continued to be praised years later (Hynes 1984). But even at the time it was published, it was written from somewhat idiosyncratic collections of insects, not from systematic inventories, in most cases. Although it included species known then in California, it was far from complete. For example, 47 additional species of stoneflies alone have been found in California since the Usinger book was first published. (At present 167 species of stoneflies are known for California [R. L. Bottorff, R. Baumann, B. P. Stark, and N. Erman, unpublished list]). In addition, revisions of systematics for nearly all groups in the book have made many changes in species names and evolutionary relationships. Further, insects, though they constitute the largest taxon of freshwater invertebrates (that is, the taxon containing the greatest number of species), are not the only invertebrates present in Sierra waters. Examples of other groups not included in the Usinger book are flatworms, nematodes, segmented worms, snails, clams, and crustaceans (fairy shrimp, crayfish, isopods, etc.).

Species Inventories and Endemism in the Sierra Nevada

We can ascertain the extent and nature of aquatic invertebrate diversity by examining taxa in a few geographic areas in the Sierra where extensive survey work has been conducted on some groups. This effort is woefully incomplete because we do not have a Sierra-wide inventory, but it is a beginning and indicates the percentage of endemism and numbers of species in some basins (table 35.1). Endemism in the context of

TABLE 35.1

Estimated number of species of selected aquatic invertebrate taxa in some areas of the Sierra Nevada (see text for references).

Taxon, by Area	Number of Species Present	Number of Species Endemic to Sierra	Percentage of Species Endemic to Sierra
Sagehen Creek Basin			
Stoneflies	38	6	16
Caddisflies	77	11	14
Mayflies	22	?	?
Cosumnes River Basin			
Stoneflies	79	16	20
Fresno, Kern, Madera, and Tulare Counties			
Caddisflies	128	11	9

this chapter means species that are found only in the Sierra Nevada. Many other species are present in the Sierra in only one or a few other places but are not strictly endemic.

Specific Studies by Location

Sagehen Creek Basin. One of the better-studied stream basins is the Sagehen Creek basin on the east side of the Sierra, north of Truckee, where the University of California has operated a field station in the Tahoe National Forest since 1951 (see also Kimsey 1996). Even here, however, some groups, namely stoneflies (Plecoptera) and caddisflies (Trichoptera), have been well surveyed, and others, for example, true flies (Diptera) and mayflies (Ephemeroptera), are still incompletely known. Stoneflies were comprehensively surveyed in 1967 (Sheldon and Jewett 1967), and the list was revised and updated for the first North American Plecoptera Conference in 1985 (R. Baumann, W. Shepard, B. Stark, and S. Szczytko, unpublished data, available from N. A. Erman). Thirty-eight species of stoneflies are known from the Sagehen Creek basin. Seventy-seven species of caddisflies have been found in the basin (Erman 1989). Twenty-two species of mayflies have been identified in the basin, but this collection has not been verified by experts on Ephemeroptera, and the actual number is probably higher (D. C. Erman and N. A. Erman, unpublished data). Aquatic habitats surveyed included Sagehen Creek (a second-order stream), springs, spring streams, temporary streams, temporary ponds, and peatlands.

For the two well-studied groups in this stream basin we have an estimate of endemism: 11 of the 77 species of caddisflies are probably endemic to the Sierra (14%), and 6 of the 38 stonefly species (16%) are endemic, based on present information.

Cosumnes River Basin. Another study of stoneflies was conducted on the west side of the Sierra throughout the Cosumnes River basin (Bottorff 1990) where seventy-nine species were found over six stream orders, from headwater streams to the major river at the lower part of the watershed (R. Bottorff, telephone conversation with the author, October 11, 1995). Sixteen of these species are endemic to the Sierra; seventeen are endemic to California. Some species endemic to the Sierra are also found in Nevada and are therefore not considered California endemics but are, nevertheless, Sierra endemics. Twenty-six of the species found in the Cosumnes River basin were also present in the Sagehen Creek basin, and four of these are Sierra endemics.

Fresno, Kern, Madera, and Tulare Counties. Extensive blacklight collections of caddisflies have been made in Fresno, Kern, Madera, and Tulare Counties, in the San Joaquin–Tulare basins, by D. Burdick and R. Gill (as reported in Brown 1993). Some species were collected by other methods. Species are reported by elevation from 30 m to 2,652 m (100 ft to 8,700 ft) above sea level. We eliminated species found only below 213 m (700 ft), synonymous species (species described more than once in the literature), and species listed as new species but for which no description exists in the literature. With these criteria, the number of caddisfly species reported by Burdick and Gill for these four Sierra Nevada counties was 128. Eleven of these species are endemic to the Sierra.

Black lights are known attractants of some insects and thus sample an unknown area. Some species are more attracted to them than are others, and day-flying species may not be collected with black lights. The results from blacklight collecting are difficult to interpret in terms of estimating the species richness of a given area or habitat. Therefore, this number is subject to revision, but it gives a general idea of west-side Sierra caddisfly species in these basins.

A comparison of this list with the east-side Sierra study of caddisflies in the Sagehen Creek basin (Erman 1989) shows that 50 species were collected in both areas and that 27 species were present in the Sagehen Creek basin that were not found in the San Joaquin–Tulare basins. Jaccard's index of similarity (Pielou 1984) showed a 32% similarity between the two areas.

With only these few comprehensive surveys and collections of Plecoptera and Trichoptera species in a given area of the Sierra, we can say little about relative diversity. Species-level surveys in other parts of the Sierra are greatly needed.

Selected Taxa of Invertebrates

A few taxa were selected for more in-depth analysis for this chapter to determine percentages of endemism in the greater SNEP study area. Taxa were selected because they have been studied recently, because databases existed and were being kept up-to-date by experts in that taxonomic group, or because a reasonably recent (since 1970) monograph had been published.

The difference between collections and surveys is important here. The total number of species for the state is based on collections. These usually consist of one-time visits to a site, with the collectors using one or two types of collecting methods. The numbers of species for the Sagehen Creek basin and the Cosumnes River basin, in the previous section, are based on surveys. A survey uses some kind of systematic sampling scheme. The sampling methods used by Sheldon and Jewett (1967), Bottorff (1990), and Erman (1989) were different, as would be expected when different groups of organisms are being sampled for different reasons, but all were year-round samplings of all habitat types. Surveys of species done in other parts of the Sierra would greatly enhance our knowledge of invertebrates and undoubtedly would reveal new species. Unless they are specifically designated as surveys, however, species numbers in this chapter are all based on collections (table 35.2).

Plecoptera (Stoneflies, Insecta). Plecoptera is one of the better known orders of freshwater invertebrates in California. It is also a small group (based on number of species) compared with the Trichoptera or Diptera. At present, 167 species are known in the state; 122 of these are present in the Sierra and 31 are endemic to the Sierra (R. L. Bottorff, R. Baumann, B. P. Stark, and N. A. Erman, unpublished list). The Sierra-Cascade system and the Appalachian system are considered the "two great centers of endemicity" for the North American Plecoptera. About 25 genera are thought to have evolved in each area (Stewart and Stark 1988). Most stoneflies are dependent on lotic habitats (running water) of high oxygen and low temperature, and so it is not surprising that their distribution would be concentrated in the Sierra.

Megaloptera (Alderflies and Dobsonflies, Insecta). Alderflies (Sialidae) are a small group of aquatic insects with only 24 North American species; 9 of these are present in the western United States (Whiting 1991a, 1991b, 1994). Six species are known from California, and one is endemic to California. Four species are present in the Sierra as well as in other parts of the state.

Eleven species of dobsonflies (Corydalidae) are known in California, and seven of these are in the Sierra (Usinger 1968; Flint 1965; Evans 1984). Sierran endemism of species in this family was not determined.

Trichoptera (Caddisflies, Insecta). The caddisflies are a large and diverse group of aquatic insects, and species are found in nearly all freshwater habitats. At present, 308 species are known in the state; 199 of these are present in the Sierra, and 37 are endemic to the Sierra (Morse 1993; J. C. Morse, personal database of published literature; N. A. Erman, personal database). The largest family of caddisflies in the state is Limnephilidae (63 species), and the second largest is Rhyacophilidae (59 species). These are also the largest and second-largest families in the Sierra. At lower elevations in warmer water, the family Hydroptilidae, the microcaddisflies, is diverse and poorly known. New species of Trichoptera will be discovered with more extensive surveys.

Diptera (True Flies, Insecta). Diptera is the most diverse order of all freshwater invertebrates. Within the Diptera, the family Chironomidae (midges) is the largest (Allan and Flecker 1993). These taxa are some of the most difficult to identify and are greatly understudied in the Sierra. Many species of Diptera are semiaquatic and spend most of their lives in the riparian area at the land-water interface.

Two small and unusual families of Diptera are discussed here, but it should not be assumed that these in any way represent the vast spectrum and diversity of Sierra Nevada aquatic Diptera. A third family of Diptera, the mosquitoes (Culicidae), is briefly discussed.

Blephariceridae (Net-Winged Midges, Insecta: Diptera). As was mentioned earlier, a family of true flies called the net-winged midges, Blephariceridae, is found exclusively in rush-

TABLE 35.2

Species estimates of selected aquatic invertebrate taxa in California and the Sierra Nevada. (Includes greater SNEP study area. See text for sources.)

Taxon	Total in California	Total in Sierra	Number Endemic to Sierra	Percentage Endemic to Sierra
Stoneflies (Plecoptera)	167	122	31	25
Alderflies (Megaloptera: Sialidae)	6	4	0	0
Dobsonflies (Megaloptera: Corydalidae)	11	7	?	?
Caddisflies (Trichoptera)	308	199	37	19
Net-winged midges (Diptera: Blephariceridae)	16	11	1	9
Mountain midges (Diptera: Deuterophlebeiidae)	6	4	1	25
Snails, clams (Mollusca)	?	40	8	20
Fairy shrimp, brine shrimp (Anostraca)	23	10	1	10

ing mountain streams, primarily in the western United States. The larvae have suction-cup-like attachments on their abdominal segments. Sixteen species (in five genera) of these flies exist in California (to our present knowledge), more than in any other state (Hogue 1973, 1987). Seven are endemic to California. Eleven are present in the Sierra Nevada (including Modoc County). All sixteen are present primarily in the Sierra and/or Coast Ranges. One species, however, is known from only one area in the northeastern corner of California (and the northwestern corner of Nevada).

Deuterophlebiidae (Mountain Midges, Insecta: Diptera). Another family of Diptera, the Deuterophlebiidae, or mountain midges, lives in much the same habitat as the net-winged midges and is present in the western mountains of North America and in eastern and central Asia. The larvae have rings of hooks on the abdominal prolegs to attach to rocks in the strongest currents. Only six species have been described in North America; four are present in the Sierra, and one is endemic to the Sierra (Courtney 1990).

Culicidae (Mosquitoes, Insecta: Diptera). Mosquito research was not analyzed for this chapter and is mentioned here only because mosquitoes have probably been studied more than any other aquatic invertebrate in California. Much mosquito habitat in the Sierra is in tree holes in the lower elevations and in snowmelt pools at higher elevations. Mosquito researchers think that reservoirs have not had a significant impact on mosquito distribution (B. Eldridge, Entomology Department, University of California, Davis, telephone conversation with the author, 1994). Mosquitoes prefer shallow water, often with aquatic vegetation, which is not the general condition of reservoirs. But discussion of possible changes in mosquito distribution caused by reservoirs is speculative because studies on this issue were not found for the Sierra. It is known that in other parts of the world reservoirs have caused epidemics of invertebrate-borne diseases and the spread of invertebrates undesirable to humans (Petts 1989).

Mollusca (Snails, Clams). Our information about mollusks is incomplete, but what is known is instructive. In 1981, thirty-two species of mollusks were known from the Sierra and northeastern California (Taylor 1981). None were endemic to the Sierra, but several had only one to a few populations in California and those were in the Sierra or northeastern California. Some of these populations were known to be extinct.

In recent years several new species of snails have been described in the Sierra. Eight recently described species in the genus Pyrgulopsis are considered endemic to the greater SNEP study area and are present in springs (Hershler 1994, 1995). Pyrgulopsis is the second most diverse genus of freshwater snails. Pyrgulopsis are widespread in the United States, and their range extends into southern Canada and northern Mexico. Seventy-two species were known and considered valid as of 1995, and eight of those were found only in a few spring systems in the Sierra Nevada study area (Hershler 1994, 1995).

Future work on mollusks will likely reveal new species of aquatic snails in the Sierra as thorough and systematic surveys are conducted, particularly on the west side of the Sierra, and as "modern" taxonomic study is used (R. Hershler, letter to the author, March 16, 1995).

Anostraca (Fairy Shrimps and Brine Shrimps). At present there are twenty-three species (six genera) of Anostraca known in California (Belk and Brtek 1995; B. Helm, personal database and conversations with the author, November 1995, January 19, 1996). Ten species are in the greater SNEP study area. Of the nine species endemic to California, three are in the SNEP study area. One is Artemia monica, a brine shrimp endemic to Mono Lake.

Fairy shrimp are generally restricted to small, fishless ponds and especially to temporary systems (Dodson and Frey 1991). Habitats of species in the foothills are probably the most threatened. These are the areas under greatest pressure from human development (Duane 1996).

Unique, Small, and Unusual Aquatic Habitats

Permanent Habitats

Some Sierra Nevada habitats, such as springs, seeps, peatlands, and small first- and second-order streams, have such a high probability of containing rare and/or endemic invertebrates and have received so little attention and protection from resource agencies that they deserve special mention. These habitats are also most likely to contain imperiled amphibians, according to Jennings (1996). Spring streams are first-order streams (though the reverse is not necessarily true) and are often isolated in mountainous watersheds. Second-order streams (formed when two first-order streams join) can also be small and isolated in steep terrain. Both stream types are found at all elevations in the Sierra; thus they are not necessarily synonymous with headwater streams.

Springs, because of their near-constant temperatures, are refuges for species from previous climate regimes. Invertebrates of both warmer and colder periods are present in springs. Thus, species living in springs are often isolated populations, far out of their present geographic range, either at much higher or much lower elevations or latitudes. They may undergo further evolution in isolated habitats, leading to new species. The more stable and long-lasting the spring, the greater the species richness and the greater the likelihood of its containing endemic species (Erman and Erman 1995). Isolated upper watershed streams have a similar probability, as do peatlands connected to these systems. Many endemic and unusual species have been found in Sierra spring systems where such systems have been studied (Erman 1981, Erman 1984a; Erman and Erman 1990; Hampton 1988;

Hershler and Pratt 1990; Hershler 1994, 1995; Holsinger 1974; Kenk 1970; Szczytko and Bottorff 1987; Wiggins 1973; Wiggins and Erman 1987).

Important to the understanding and management of these systems is that they are different from one another and are in close contact with the surrounding land. In a study of fourteen springs within one second-order (upper watershed) stream basin we found a similarity of only 25% among caddisfly assemblages in the various springs (Erman and Erman 1990). The springs differed widely in species richness and species composition. Some endemic species were present in only one or a few springs. The management implications of these findings are that spring "types" cannot be identified and set aside to protect or preserve species. In other words, all Sierran springs need some protection or consideration in land management.

The greatest threat to spring species in the Sierra today is probably livestock grazing because it is so all-pervasive and invasive to small, wet areas (Erman, unpublished information, S. Mastrup, California Department of Fish and Game, telephone conversation with the author; D. Sada, private consultant, telephone conversation with the author). But logging, road building, water development, dynamiting, wildfire, and other impacts in the vicinity of springs can affect riparian vegetation, water volume, timing of flow, chemical concentrations, solar radiation, and temperature regimes, making springs and spring streams uninhabitable to species restricted to them (Erman and Erman 1990).

One of the more ironic uses of headwaters is a multiagency (California Department of Fish and Game, Nevada Department of Wildlife, U.S.Fish and Wildlife Service, Pacific Southwest Region of the U.S. Forest Service [USFS] and Intermountain Region of the USFS) plan for spring streams to serve as safe holding areas for endangered fish. Headwater areas are poisoned prior to becoming repositories for fish that, in some cases, were not historically present (Gerstung 1986). Threats to unusual and endemic invertebrates under such a fish management scheme are apparent. This plan is an example of the fallacy of single-species management.

Temporary Habitats

Temporary aquatic habitats have been largely unprotected in management plans. While not rare in the Sierra, these habitats can have unique assemblages of invertebrate species. Temporary streams, ponds, and springs are not always recognized as aquatic habitats during dry seasons or periods, another reason they may be overlooked. Invertebrates that use temporary habitats have been studied somewhat in the Sierra (Abell 1957; Erman 1987, 1989; Szczytko and Bottorff 1987) and in western Oregon (Anderson and Dieterich 1992; Dieterich and Anderson 1995). Some species are confined to temporary habitats and require a drying phase to complete their life cycles. Such invertebrates are often widespread because of dispersal mechanisms evolved in response to variable habitats but not always (e.g., Szczytko and Bottorff 1987).

In addition to their importance for unusual invertebrates, temporary habitats can be areas of high invertebrate biomass and important spawning areas for fish. In the Sagehen Creek basin (on the east side of the Sierra), an intermittent stream that dries completely in most summers is the spawning ground for one-third to one-half of the rainbow trout population of the stream system (Erman and Hawthorne 1976). During the dry season, this streambed is grass covered and unrecognizable as an aquatic habitat.

The greatest threats to temporary aquatic habitats at present are logging operations and roads. These habitats should be treated as if they were permanent in terms of management protection: they are the habitat for species restricted to temporary water. Furthermore, intermittent or ephemeral streams connected to a permanent stream system are just as capable of transporting sediment downstream into larger streams as are permanent streams.

Aquatic Invertebrates as Monitoring Tools and Habitat Indicators

Values of Broad Taxa Invertebrate Monitoring

Invertebrates have been used as monitoring tools to assess water conditions for more than eighty years. Much of our knowledge about aquatic invertebrates in the Sierra and in California has come from this use. When using invertebrates as indicators of aquatic conditions, ecologists study a large assemblage of species at a site but identify and group species only at a broader taxonomic level (genus, family, order, or class). As water conditions change, some groups rise in numbers, others fall, and some may disappear or appear. As was discussed earlier, detrimental change due to some impact is usually in the direction of a decrease in organism size and a decrease in taxa richness (higher numbers of small species, fewer large-sized species, and perhaps fewer species overall, depending on the degree of impact [Wallace and Gurtz 1986; Grubaugh and Wallace 1995]).

One continuing, long-term study of logging impacts on invertebrate assemblages has been conducted in California since 1973 (Erman et al. 1977; Newbold 1977; Roby et al. 1977, 1978; Newbold et al. 1980; Erman and Mahoney l983; Mahoney 1984; Mahoney and Erman 1984a, 1984b; O'Connor 1986; Fong, 1991). This study was conducted on 62 stream sites initially; 22 were in the Sierra Nevada. Logged and control (reference) streams were blocked into groups of three or four by geographical location, stream size, vegetation, stream morphology, and geology. Aquatic invertebrate assemblages were used to determine the effects of logging on streams and the effectiveness of wide and narrow buffered areas in protecting streams. The measurements used were diversity indices that examined invertebrate taxa richness and evenness of numbers within taxa. The study has been continued for two decades to assess stream recovery.

Major findings of the study were that the numbers of midge larvae (Chironomidae), the small mayfly Baetis spp., and small nemourid stoneflies rose significantly following logging in streamside zones without buffer strips, a result of increased sediments, increased light from loss of riparian vegetation, and increased algal growth (Erman et al. 1977).

Discrete, local disturbance from failed road crossings associated with logging caused a decline in the number of taxa downstream. Where wide buffer areas (strips) were left unlogged along the streams, invertebrate communities showed little difference from those of unlogged streams. However, narrow buffers incompletely protected streams, and the narrower the buffer, the greater the impact of logging on stream invertebrate communities. High levels of stored sediment remained in the set of streams logged without buffers when the streams were resampled five to six years later and compared to control streams. Full recovery of invertebrate communities required nearly twenty years after the initial disturbance from logging. A significant footnote to these long-term studies is that the control streams gradually were lost as controls because of further logging in the watersheds. New controls for research were established where possible.

Other impact studies in the Sierra that have used aquatic invertebrates cover a broad spectrum of subjects. A few examples are (1) the potential effects of copper in water (Leland et al. 1989); (2) the potential effects of acid deposition (Jenkins et al. 1994) (note that increased acidity in Sierra waters is not currently considered a problem according to Cahill and colleagues (1996); (3) the effects of suction dredge gold mining (Harvey 1982; Somer and Hasler 1992); (4) the effects of channelization (Moyle 1976); (5) the effects of fish introductions (Reimers 1979); (6) the effects of visitor use on high-mountain lakes (Taylor and Erman 1980); and (7) the effects of wildfire (Roby and Azuma 1995).

Limitations and Cautions of Broad Taxa Invertebrate Monitoring

A great deal of time, effort, and money have been spent on sampling and analyzing invertebrates from stream-bottom substrates in the Sierra Nevada. Much of this work has been conducted or funded by state and federal resource agencies (the U.S. Forest Service, California State Fish and Game, Bureau of Land Management, etc.). Most if it is in unpublished reports in agency files. Examples of such studies have been examined for this report. Problems of incomplete understanding of invertebrate sampling and what it can currently tell us in California are evident in the conclusions drawn from some of these efforts. Nevertheless, such sampling, if conducted with care and adequate controls, can serve as baseline work for future studies and should not be abandoned but rather expanded and conducted at more sophisticated levels in the Sierra.

In California several entities (e.g., timber companies, state agencies, citizen groups) are beginning programs in invertebrate monitoring to assess watershed condition. Therefore, a few points seem worth reviewing in regard to future studies in the Sierra Nevada and what such studies can reveal.

The natural variability of invertebrate assemblages in streams is poorly known in the Sierra. One-time or one-season invertebrate sampling cannot reveal the "health" of a stream or the extent of cumulative impacts in a stream basin at present. Changes over time in taxa richness and other various indices can show the direction of effect (i. e., are conditions worsening or improving?). Invertebrate sampling is a useful tool in stream monitoring if controls (references) in time and/or space (depending on the objectives of the study) are established, and if the limitations of stream-bottom substrate sampling are understood. Many papers and several books have been written on this subject (e.g., Plafkin, et al. 1989; Rosenberg and Resh 1993; Loeb and Spacie 1994), and a complete airing of the issues is beyond the scope of this chapter.

Stream-bottom samples, for the most part, cannot tell us what species are in streams. Species can be determined only from sexually mature forms for most aquatic invertebrates. The large majority of aquatic invertebrates (both biomass and species) in Sierran streams are insects, and the sexually mature form of most aquatic insects is the flying terrestrial adult. These adults are not collected in stream-bottom samples. Furthermore, the large majority of species descriptions for aquatic insects are based on males only, and so male adults are needed to determine species (Wiggins 1990).

Species identification becomes critical when invertebrates are being sampled to determine if a project or if cumulative impacts from many uses are having a permanent effect on species composition. The current interest in biodiversity and curbing the loss of species demands more rigorous analysis of invertebrates than is presently being conducted by resource agencies, universities, and consultants in California.

Recent examples of unproven conclusions based on invertebrate sampling are found in state documents for the continued use of rotenone in streams (CDFG 1994a, 1994b, 1994c). These documents and their use of supporting studies reveal a confusion between species and overall aquatic invertebrate assemblages. Invertebrate studies cited in the first two documents (1994a, 1994b) monitored not changes in numbers of species but rather changes in the numbers of larger taxonomic categories (e.g., order, family, or genus) of invertebrates. And the following statement is made in the Kern River negative declaration (CDFG 1994c): "Aquatic invertebrate populations will become reestablished in a few months. The species composition may be different initially and may require several years to return to the pre-project status." However, pre-project species composition was not determined for invertebrates. (It is not possible for species to "return to the pre-project status" if they have become extinct, and with the study that was conducted, we have no way of determining that.) These comments are not meant as a criticism of the original studies, but rather are meant to serve as a cautionary note about drawing conclusions that were not tested and then applying those conclusions to management policies.

Sampling must be appropriate for the question being asked. Many studies use sampling and analysis techniques merely because they provide numbers, with little regard for what is being sampled. An example is the use of invertebrate drift sampling as a general monitoring method in streams, without an understanding of the many natural causes of invertebrate drift. Another example is the rather arbitrary assignment of taxa (usually genus or family) to a functional feeding group. (Functional feeding groups are broad categories based on how invertebrates feed and can indicate broad trends in energy inputs to a stream system.) But what such categories indicate about stream conditions is questionable in the Sierra without controls and baseline data. A second problem with functional feeding groups in California is that they are based on general and incompletely researched tables from textbooks (e.g., Merritt and Cummins 1984) rather than on actual food-habit studies of the species (usually unknown) in question. Functional feeding groups may vary among species within a genus (that is, different species within a genus may feed in different ways) and with larval instar (stage) (Thorp and Covich 1991).

An example, for purposes of illustration, is the genus, Dicosmoecus, perhaps the most studied caddisfly genus in the western United States probably because of the large size of the individuals. Three species of the genus are present in the Sierra, sometimes in the same stream system (Erman 1989), but they live in different habitats. Dicosmoecus gilvipes feeds predominantly on diatoms and fine particulate organic matter by scraping substrate material. D. atripes and D. pallicornis feed largely on vascular plants and animal materials and are considered generalized predator-shredders (Wiggins and Richardson 1982). D. gilvipes is tolerant of warm temperatures, unshaded streams, and sedimentation. The other two species are present in cooler, shaded, undisturbed areas. The larvae of the three species are difficult to separate and are probably often confused. Conclusions about habitats or impacts based on larval identification or presumed functional feeding group could be quite misleading in this case.

A second example is of two caddisfly species with overlapping distributions in small Sierran streams, Farula praelonga and Neothremma genella (Trichoptera:Uenoidae). These two species, though in different genera, are difficult to separate as larvae except where they have already been studied (Wiggins and Erman 1987). F. praelonga reaches larval maturity in the winter and emerges as an adult in early spring, while N. genella matures through the summer and emerges in the autumn. Both feed by scraping diatoms from rocks. F. praelonga, the more rare of the two species, is most abundant in shaded areas with constant temperatures near spring stream sources, whereas N. genella reaches larger population numbers somewhat farther downstream from the source and in more open areas (Erman and Mahoney 1983; Wiggins and Erman 1987). Therefore, these two species, though in the same functional feeding group, would be affected differently by land management that, for example, opened the riparian canopy or changed water temperature.

Correct identification even of genera or families of invertebrates requires expertise, a knowledge of invertebrates, good up-to-date taxonomic keys, and knowledge of how to use the keys. Reference collections (sometimes called voucher specimens) are necessary to confirm identities of invertebrates from past studies. Taxonomy changes as groups of organisms are revised by experts. Without preserved specimens, studies from ten or twenty years ago become questionable, and there is no way to verify whether or not the taxa were correctly identified initially. These taxonomic changes or misidentifications probably would not affect the results of impact studies but would affect our knowledge of changes in species diversity, that is, of whether a species has disappeared over time.

Many habitat factors affect natural variability. Invertebrate assemblages can change rapidly over rather short distances if there are changes in light, temperature, substrate, water chemistry, elevation, and so on. An example from a study of Sierran spring streams illustrates this point. In one undisturbed spring stream, caddisfly (Trichoptera) species similarity between the spring source and a point 270 m (886 ft) downstream was only 38% (using Jaccard's index of similarity [Pielou 1984]). At 450 m (1,476 ft) downstream, species similarity with the spring source dropped to 20%. In another nearby spring with more water, less light, and lower temperature, caddisfly species were replaced less rapidly: similarity was 40% at 1000 m (0.6 mi) downstream and fell to 22% at 1,800 m (1.1 mi) downstream. Results were based on adult emergence traps, operated for a year on the first spring stream and for nineteen weeks through summer and autumn on the second spring stream. These two springs are near each other (about 1,600 m [1 mi] apart) in the same second-order stream basin and emerge from the same hillside, and yet the species similarity between the two spring systems was only 28% (Erman 1992b). Both were relatively protected from anthropogenic influence and had been for many years prior to the study.

This example may be somewhat dramatic because of rapid physical changes in small stream systems, but it nevertheless illustrates natural species replacement over a stream gradient and natural differences among nearby small, upper watershed streams.

If natural variation over a sampling gradient is not determined or accounted for, it can result in a study either underestimating or overestimating impacts to the invertebrate assemblage. Habitats already undergoing significant impacts may be selected as controls (references) and, thereby, underestimate the effects of some activity or project on the aquatic biota. Or, conversely, habitats naturally low in species (snowmelt streams, variable springs) may be considered degraded when they are not.

A recent survey of thirty-one Sierra Nevada streams from the north to the south Sierra was unable to detect the effect of cumulative impacts on invertebrate assemblages (based on one-time sampling at all but two sites), because natural variation over so broad an environmental gradient masked the effects within stream basins (Hawkins et al. 1994). An earlier study (Erman et al. 1977; Newbold 1977) had also concluded that natural variation rather than logging or disturbance effects accounted for variation in invertebrate assemblages when data were analyzed using multivariate analysis. However, in the earlier study, the effects of logging and buffer strips were clearly evident when streams were grouped by treatments and controls in the same geographic area. Further analysis of the Hawkins team's work must wait until the invertebrate data are published.

In conclusion, many levels of aquatic invertebrate monitoring are available for assessing environmental changes. The impacts on invertebrate assemblages of many land and water uses are known, and major changes have likely occurred in invertebrate assemblages in Sierra waters. But at present, we have little baseline information in the Sierra to know whether aquatic invertebrate species are being lost.

General Status of Aquatic Habitats

Currently, aquatic habitats are the most altered and threatened biotic communities in the state (Jensen et al. 1990). Recent forest plans contain reviews of conditions in the national forests. A few summaries are given here as examples of conditions, but no attempt has been made to review the aquatic analysis of all the forest plans. The plan for the Plumas National Forest (USFS 1988) found that one-third of the running-water fish habitat in the forest was in poor condition, 78% of it in small streams. Nearly half, 47.6%, of the small stream acreage was in poor condition. Only 20% of all running-water fish habitat in the Plumas National Forest was in good condition, according to the Forest Service's own assessment.

In the plan for the Stanislaus National Forest (USFS 1992) only two of sixteen watersheds were in very good condition. "Fair" and "poor" watersheds were lumped together, perhaps suggesting that there were more poor than fair watersheds. Analysis of aquatic habitat was less thorough in the Stanislaus plan than in the Plumas plan. Water projects were omitted from the discussion of cumulative watershed effects. Impacts of livestock grazing on streams were not analyzed in the plan, although 82% of the forest was grazed.

In the Modoc National Forest, 78% of riparian areas were in fair or poor condition in 1988 (U.S. General Accounting Office 1988).

The focus of resource management on game fish production poses a significant conflict with invertebrate diversity in Sierra waters (see also Knapp 1996; Moyle et al. 1996). Environmental assessments for projects of many types (e.g., hydroelectric projects, rotenone projects, proposed timber harvest operations, hydraulic mining regulations, Board of Forestry rules) have been reviewed for this chapter. None have contained adequate or realistic assessments of impacts to aquatic invertebrate communities; in most, there were no assessments. Projects are analyzed based on whether or not game fish (usually brown or rainbow trout) will be affected. Money and resources are directed toward that analysis objective. Little effort is made by state and federal agencies to protect species of no known economic value or species with few human defenders. More significant, however, is the apparent lack of understanding of the complex physical, chemical, and ecological processes and cycles that interact to determine the fate of biotic communities in Sierra aquatic habitats.

These assessments are not encouraging with regard to present trends in Sierra Nevada aquatic environments, but by admitting the problems and analyzing how they occurred, we can move on to restore degraded habitats and prevent the same problems in the habitats that are still in good condition.

Institutional Responsibilities

An assessment of aquatic habitats in the Sierra must include an assessment of the institutional management of those habitats. Many state and federal agencies have jurisdiction over the streams and wetlands of the Sierra, whether the land is privately or publicly owned. Such agencies as the California State Water Resources Control Board (the state water board) and its regional water quality boards, the Water Resources Agency, the California Department of Forestry, the Board of Forestry, the California Department of Fish and Game, Caltrans, the Fish and Wildlife Service, the Federal Energy Regulatory Commission, the U.S. Forest Service, the Bureau of Land Management, the Bureau of Reclamation, the Army Corps of Engineers, and many local county and city planning agencies all have authority and responsibility, regulations and laws governing Sierra waters and riparian areas. Evaluating the performance and effectiveness of these agencies is essential to improved watershed protection. How well are our present extensive regulations and laws working? How well are they obeyed and enforced? Do agencies communicate with one another and coordinate their efforts? Are agency decisions based on current scientific knowledge? Is continuing education encouraged within the agency? Do agencies recognize and admit resource problems and have the will to change? Do agencies evaluate their own past performance and effectiveness? How do they view the California Environmental Quality Act and the National Environmental Policies Act? Are agencies following the spirit as well as the letter of the law? Do they make decisions in an open and democratic manner? Do they welcome public input?

The answers to these questions are connected to and are crucial to the present and future status of the biota in Sierra waters.

FUTURE NEEDS

Future needs for the study and protection of aquatic and riparian habitats and, by implication, the status of aquatic invertebrates in the Sierra are in the areas of research, management, and institutional evaluation. The following recommendations are derived largely from the issues discussed earlier in the chapter.

Establish Reference Streams and Baseline Data

Aquatic habitat research for the Sierra should include the establishment of undisturbed reference streams and other aquatic sites to be monitored over time (controls). Streams in national parks may be the only reference sites remaining in the Sierra that are close to "natural" or undisturbed conditions, but they do not represent the full range of vegetation, elevation, and other Sierra Nevada stream conditions. We need to establish control sites in many parts of the Sierra, and this goal will require cooperation among many agencies.

We need complete aquatic invertebrate inventories and surveys, especially in undisturbed (or nearly undisturbed) sites to compare with disturbed (managed?) areas. University field stations could contribute substantially to this effort if they would make the commitment to undertake surveys at the species level. Few Sierra field stations have attempted to inventory aquatic invertebrate species. Where inventories have been conducted, they have been the specific interest of individual researchers and not a concerted university field station effort.

Improve Monitoring

Monitoring of stream invertebrates could be conducted at a more knowledgeable and meaningful level. Sampling to determine species and verification by taxonomic experts could make a significant contribution to our baseline knowledge of freshwater invertebrate diversity in California. Studies must be reproducible for long-term biomonitoring. We may not have the institutional organization in California at present to accomplish this level of research. California needs a natural history survey modeled after those of some eastern states (i.e., the Illinois Natural History Survey, and the Ohio Biological Survey). In some states these organizations are supported by private funding. An expanded role for the California Academy of Sciences could be explored in this regard.

Consider All Biota and All Impacts

We need better, more credible analysis of impacts to the entire biota. There are dangers in single species or even single-taxon management. There are also dangers in single-project review. The impacts of small hydroelectric projects or rotenone poisoning or grazing allotments or logging operations must be assessed in their entirety throughout the Sierra and for their cumulative and interactive impacts with one another. We need waterscape as well as landscape analysis.

Mechanical, species-specific means of removing unwanted exotic species should be encouraged. Chemical and mechanical methods that indiscriminately kill many species should be discouraged.

Value Citizen Groups

Citizens groups interested in watershed monitoring could be (and are) involved in identifying cumulative impacts; resource agencies should welcome this enormous source of energy and local expertise.

Recognize Problems with Reserves

We probably cannot protect aquatic diversity by setting aside reserves or key watersheds. We do not have the information at this time to determine what areas could serve as reserves for aquatic invertebrates, and it is unlikely that we ever will. We do not know the minimum habitat required to maintain genetic viability of aquatic invertebrate species. Rare and endemic aquatic invertebrates likely occur in every watershed in the Sierra, making every watershed "key" for some species. Endemic aquatic invertebrates are isolated in smaller streams and other small aquatic habitats throughout the Sierra. River basins are continuous systems; what happens upstream affects the downstream biota. Setting aside a piece of a stream or watershed for protection is not a long-term solution, though it may have some immediate benefits. Influences outside the boundaries of reserves (ground-water pumping, air pollution, changes in the ozone layer, exotic species, diseases, burgeoning human population) require us to consider issues far beyond the boundaries of reserves or watersheds and even beyond the Sierra. In short, reserves or key watersheds give a false sense of security about species conservation. Our best hope is to improve analysis, monitoring, and management; protect unspoiled areas; and work toward protection and restoration of all watersheds.

Concentrate on What We Can Change

We must concentrate on what we can change and what we know is having a negative impact on aquatic systems. Sedimentation from logging, roads, livestock grazing, construction of many kinds (housing, ski resorts, hydroelectric projects), and mining is a large problem in the Sierra and causes significant changes in invertebrate assemblages, as was discussed earlier. Reducing sediment in aquatic systems should become a major objective of resource agencies. "Sediment load and deposition constitutes one of the most serious water quality problems throughout the world" (Osborne and Kovacic 1993).

Evaluate Pulse and Press Disturbances

There is a need to recognize the difference between "pulse" disturbances (limited and definable duration) and longer-induration "press" disturbances (Bender et al. 1984; Niemi et al. 1990). Not surprisingly, streams recover more rapidly from pulse disturbances. But recognizing when pulse disturbances may become a continuous press on the system is important. For example, a logging operation that temporarily increases stream sediment or light is a pulse impact from which the system likely will recover within a few years. But continuing logging operations throughout a basin, or a broad network of roads, or a reservoir, or an old mining scar carrying sediment into a stream year after year, or continuous livestock grazing, or all of these together in a watershed become press disturbances and may irrevocably alter habitat and the biota.

Protect Upper Watersheds and Small Aquatic Habitats

Upper watershed streams and small aquatic habitats need far more protection than they are currently receiving. Buffer areas should be increased and should be dependent on landscape factors (slope, soils, geology) as well as stream size. In other words, the steeper the slope, the greater the buffer area should be regardless of stream size. The smaller the water body, the closer its connection to the surrounding land, and the more likely it is to be damaged by activities on the land. Present logging buffers required on private land for small streams are woefully inadequate, but also inadequate are buffers for small streams on public land. To protect the watershed, we must protect the headwaters.

Riparian areas are critical to aquatic habitats and the aquatic biota, and conversely the aquatic biota is a critical food supply to terrestrial animals that inhabit riparian areas. Riparian areas should not be abrupt and isolated zones, as they are presently in many logged areas, but should grade gradually into upland areas.

Protect Temporary Aquatic Habitats

Temporary water should receive the same protective safeguards and buffer areas as permanent water. There is as much biological justification for protecting temporary water as there is for protecting permanent water.

Reduce Total Roaded Area

Total roaded area should be reduced. Road construction around wetland and riparian areas needs more careful scrutiny.

Reduce, Eliminate, or Change Livestock Grazing

Cattle should be eliminated or greatly reduced in riparian and aquatic areas. Sheep should be moved rapidly through wet meadows and spring areas. No grazing of livestock should occur in peatland fens.

Restore Habitat Where Possible

Restoration should focus on eliminating the source of a problem. Some impacts to the Sierran waterscape are beyond complete restoration, but partial restoration may be possible. For example, large reservoirs are permanent and have an enormous impact on river systems; nevertheless, hydrologic regimes can be altered to more normal flows. Some streams, buried by mining spoils, may be beyond recovery.

Do Not Manage Riparian Areas for Fire Protection

Wildfire cannot be anticipated in riparian areas. Therefore, measures taken to prevent wildfire in riparian habitats may cause more harm than good by adding road systems and sediment, by decreasing wood and downed snags, and by opening riparian areas and changing the moist microclimate. Aquatic habitats will be better protected by preventing the known damage caused by known and predictable human activities than by trying to fire proof riparian areas.

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