Global Biodiversity in a Changing Environment
Scenarios for the 21st Century

F. Stuart Chapin III
Osvaldo E. Sala
Elisabeth Huber-Sannwald
Editors

Ecological Studies 152
Introduction

James Reynolds and Frank L. Koehl
Lyle K. Metrew, Mark W. Oswood,
P. S. Laue, K. D. Faunce, K. H. O. Wimahler,

14. Fish Diversity in Streams and Rivers
known in terms of distribution and ecological sensitivity. Although we will focus on fishes in our discussion of biotic responses to climate and land-use changes, we emphasize that changes in fish species diversity are a small part of community and ecosystem responses to environmental perturbations.

The most important factors that regulate species diversity from local to regional and continental scales include history, temperature, hydrology, and geomorphology. Local diversity is strongly affected by regional diversity (Moyle and Herbold 1987; Hugueny and Paugy 1995; Angermeier and Winston 1998), which, in turn, reflects phylogenetic history (Tonn et al. 1990; Brooks and McLennan 1993). Because speciation typically requires geographic isolation for long periods, diversity is higher in regions that consistently have provided appropriate habitat through previous cooling and warming periods. For example, high diversity in the southern Appalachian region of North America and the Guyana Shield region of South America reflect the occurrence of persistent refugia during glacial advances or associated dry periods. Some of the regional variation in the diversity of riverine fishes can be explained by the accessibility of thermal or hydrological refugia. For example, fish diversity is greater in temperate North America than it is in Europe in part because north–south dispersal corridors were available to fishes in the Mississippi River basin, but not to fishes in European basins (Briggs 1986).

Thermal regimes have strong effects on species diversity in fluvial ecosystems. Relatively few species tolerate low temperature extremes coupled with a wide annual range of temperatures, resulting in the well-known inverse relationship between diversity and latitude or elevation (Winemiller 1991; Oswood et al. 1995). As thermal regimes shift with latitude and altitude in response to climate change, so will biotic distributions. Because dispersal through fluvial systems is often constrained by natural or artificial barriers (e.g., waterfalls, rapids, dams), accessibility to suitable thermal habitats during global warming may be limited. Thus, climate change generally will reduce regional species diversity over the short term.

The hydrological regime (i.e., the spatial and temporal distribution of runoff and groundwater) regulates the availability of suitable habitat and influences species diversity. For example, rivers and streams that experience very low (or no) flows on an annual (or nearly annual) basis typically support fewer species than perennial rivers and streams in the same biogeographic region (Cross and Moss 1987). At regional scales fish diversity is strongly positively related to amounts of precipitation (McAllister et al. 1986) and, perhaps, inversely related to wide variability in flow conditions that create habitat bottlenecks (Lake, personal observation). Geographic shifts in hydrological regimes caused by climate change will induce shifts in the distribution of fluvial species, most likely resulting in reductions of the regional diversity of species adapted to local hydrological conditions.

The geologic setting of fluvial ecosystems interacts with the hydrological regime to determine the geomorphology of the valley and channel which, in turn, controls the range of habitats available to the biota (see Dunne and Leopold 1978). Rivers flowing through unconsolidated materials in unconstrained valleys create and maintain alluvial floodplains, which provide a variety of productive wetland habitats that enhance the diversity of fluvial species. In general, alluvial habitat, channel size, and discharge increase in a downstream direction, resulting in increasing fish diversity as stream size increases (Sheldon 1968; Lake 1982; Welcomme and de Merona 1988).

In combination, temperature, hydrology, geomorphology, and associated riparian vegetation form a habitat "template" (sensu Southwood 1977) that controls the persistence and diversity of species at local and regional scales (Poff and Ward 1990). Maximum regional diversity is further regulated by historical constraints, including previous climatic bottlenecks and barriers to dispersal. Global changes in climate and land use will modify these regional templates, thereby altering ecosystem processes and patterns of species diversity (Grimm 1992; Poff 1992; Meyer et al. 1999; Lake et al. 2000).

The climatic, geologic, and vegetative features used to delineate biomes on a global scale clearly influence the structure and function of fluvial ecosystems that flow through them (see Minshall 1988). Biome classification, however, may not adequately reflect variation in aquatic biodiversity because streams and rivers are largely linear systems that span more than one biome and provide corridors for species movement (if barriers are absent) across biome boundaries. Environmental factors that directly regulate species diversity can also vary independently of biomes. For example, river hydrological regime, considered to be a "master variable" that limits the distribution and abundance of fluvial species (Power et al. 1995), shows considerable variation within biomes, such that streams in different biomes may be hydrologically more similar than streams within the same biome (e.g., see Poff 1996) due to natural interstream variation in gradient, groundwater inputs, vegetative cover, and so forth. Thus, a narrow focus on the biome scale as the unit of fluvial diversity response to global change is not adequate. We will organize our discussion here along two major template axes: a temperature gradient (tropical to temperate to polar) and a precipitation gradient (wet to dry regions). We will use selected biomes as examples along these axes where appropriate.

Humans Modify the Factors that Regulate Species Diversity in Rivers

Rivers and their floodplains represent areas of concentrated human economic and cultural activities, which pose significant threats to riverine diversity on local, regional, and global scales. Agricultural and urban development, pollution from industrial and domestic wastes, and dam construction have dramatically altered natural templates in rivers throughout the world, with documented reductions in diversity (Nehlsen et al. 1991; Allan and Flecker 1993). The natural connectivity of river corridors has been inter-
Figure 14.1: Hydrologic changes under climate change. The figure shows the projected changes in the hydrologic cycle under different climate change scenarios. The green region represents areas with a decrease in precipitation, while the blue region shows areas with an increase.

Hydrologic-Climatic Response to Global Changes in Climate

Petersen (1992): New insights into natural occurrences that are already under stress (e.g., hills and flood plains) lead to the need for a reevaluation of the hydrologic cycle. Recent studies have highlighted the importance of human activities in modifying the natural hydrologic processes. The figure above illustrates the potential impacts of climate change on the hydrologic cycle, emphasizing the need for adaptive management strategies.
conditions in the summer with occasional tropical storms; however, flooding is typically restricted to the winter as the result of cyclones from the northern Pacific.

Several studies have documented how past climate change altered stream and river hydrology. For example, higher frequencies of episodic super floods in the southwestern United States coincided with historical global temperature changes (Ely et al. 1993). Knox (1985, 1993) showed that a decline in regional precipitation induced by climatic changes during the Holocene affected flood frequency patterns for streams in the Upper Mississippi Valley and that these changes had a dramatic impact on channel morphology (and thus potentially physical habitat characteristics for the biota). Other studies have documented pronounced impacts of El Niño/Southern Oscillation (ENSO) events on the flooding patterns of the Amazon River (Richey et al. 1989), as well as on floods and droughts in rivers of Australia, India-Pakistan, and Africa (Whetton et al. 1990). Burn and Arnell (1993) reported several distinct historical periods showing increased flooding associated with ENSO events across many hydroclimatological zones.

It is therefore important to consider possible changes in the magnitude, duration, frequency, and timing of flows in channels and onto floodplains in response to climate change. The hydrological response of a particular river reflects modifications in the dominant hydroclimatic regime, alterations in the dominant mode of precipitation (e.g., rain vs. snow), and changes in factors that affect runoff (e.g., vegetation and land use). Predictions of the effects of projected climate changes on global river runoff and flooding patterns are unfortunately too few to allow regional predictions of how river templates will likely respond to climate change (Arnell 1996), although some regional exceptions exist (Fowler and Hennessey 1995).

Although effects of climate change on seasonal patterns in runoff cannot be generally examined in detail, studies of climate change have simulated impacts on average runoff rates for particular river systems. Changes in average precipitation may also be related to changes in extreme flows, and a change in precipitation variation may have a marked effect on the temporal patterns of discharge (Arnell 1996). For example, the Ob’-Irysh Basin may experience a modest increase in discharge in its lower river reaches (Neilsen and Marks 1994). If this effect is combined with increased rain (vs. snow) due to higher temperatures and an earlier spring (e.g., Myneni et al. 1997), then peak runoff may be reduced and may occur earlier in the year. In the Missouri–Mississippi system, runoff is not predicted to change significantly with climate change; however, because snowmelt contributes importantly to early spring flooding, elevated spring temperatures could reduce flood peaks and increase the duration of spring flooding, or cause an earlier snowmelt and reduce late summer baseflows. In the Amazon Basin, regional runoff is predicted to increase by approximately 10%, potentially increasing the levels and duration of flood peaks (Neilsen and Marks 1994). Precipitation is predicted to decrease in California, thus exacerbating current semi-arid conditions. As a result, longer dry periods could result in the drying of normally perennial streams.

Variation in ecological responses to changes in discharge and thermal regimes within large hydroclimatological regions can be expected, due to sub-biome scale features that regulate biological responses. For example, local geological conditions that regulate channel slope, floodplain development, and groundwater storage can greatly affect the availability of local refugia from such environmental extremes as floods and droughts. Many species have limited distributions within biomes or hydroclimatological regions; therefore, it is important to consider how rivers and streams within larger regions may respond to global climate and land-use changes. All these potential hydrological modifications can be exacerbated by human activities that alter the hydrologic cycle.

Fish Species Responses to Global Climate and Land Use Changes

Aquatic species, when faced with changing environmental conditions, may respond in one of three ways. First, they may adapt to the new conditions. Assuming the gene pool contains adequate variability, adaptive changes must occur at a rate sufficient to keep pace with environmental change. Global climate change and land-use conversions are occurring at a rate comparable to the greatest rates documented for previous periods of natural climatic change, when mass extinctions occurred. It is therefore highly unlikely that most fluvial species will be able to adapt quickly to such rapidly changing conditions. The second response would be shifts in the present distributions of species. This kind of response was probably very important in earlier periods of climate change (e.g., glacial and interglacial periods in the Pleistocene) (e.g., Briggs 1986). Many present patterns of species diversity and distribution can be understood in light of the historical availability of refugia from harsh conditions imposed by a changing climate. If species are able to redistribute themselves along river corridors as global change occurs, then extensive extinction could be averted. Thus, the regional response of fish species to global climate and land-use change will largely depend on the availability and accessibility of suitable refugia from changing environmental conditions. Third, if climate and land use changes produce environmental conditions beyond the tolerance limits of extant species, and refugia are not available or accessible, then extinctions are very likely.

Tropical Systems

Wet Tropical Regions

Tropical freshwaters are a major reservoir of global fish diversity. In South American fresh waters alone, more than 2400 fish species occur (Lowe-
established in the catchment and stream waters became turbid (Winemiller, personal observation). Projected regional-scale conversions of tropical woodland to agriculture, extensive drainage of wetlands, and other human development impacts (e.g., nonpoint source pollution, dams, and water extraction schemes) clearly pose a severe and immediate threat to the survival of species and ecosystems in the Tropics, which is where such a large fraction of the earth’s freshwater fish diversity resides.

Dry Tropical Regions

Savannas typically dominate landscapes in semi-arid tropical climates. We will use the riverine fish communities of African savannas as an example of global change threats to tropical fishes in semi-arid regions.

Faunal assemblages in the rivers of African savannas are dominated by widespread and opportunistic taxa with generalized food habits, as well as high growth and colonization rates. Fish faunas are dominated by cyprinids with important contributions by the Cichlidae, Characidae, Mormyridae, and various catfish families (Greenwood 1958; Lowe-McConnell 1975; Skelton 1988). Most of these fish are generalized invertivores or omnivores. Many riverine fish species undergo upstream spawning migrations during rising water periods, and their young often grow and develop in upstream or floodplain habitats (van Someren 1962; Welcomme 1985). Riverine environments also support diverse amphibian, reptile, bird, and mammal species (Cooper 1996).

With the exception of rivers draining lakes and reservoirs (e.g., the Victorian Nile), discharge in most rivers and streams varies tremendously (by an order of magnitude) throughout the year, reflecting seasonal changes in rainfall (Cooper 1996). Many arid and semi-arid areas have intermittent or ephemeral streams and rivers, and even moderately large rivers may dry up during droughts. Temperatures at elevations less than 1500 m are usually greater than 20°C (Vanden Bossche et al. 1990), and many rivers in arid or semi-arid areas are turbid, largely because of the removal of native vegetation by human activities (Dunne 1979).

The IMAGE projections indicate that average temperature changes will be small over the next century in tropical Africa (less than 1°C). Other climatologists, however, have projected temperature increases of up to 2-4°C for this region in response to a doubling of atmospheric carbon dioxide (Mkanda 1996; Unganai 1996). Because temperature conditions determine sex ratios in the developing eggs of some reptiles (e.g., crocodilians, turtles), even small temperature changes may affect the sex ratios and population sizes of reptile populations (Bull 1983). Crocodiles are apex predators in some savanna rivers; therefore, these temperature effects may have repercussions for the rest of the community. Because many of East Africa's rivers flow west and east, fish species cannot migrate latitudinally in response to temperature changes. Many African rivers, however, have their headwaters in high mountains and show large elevational changes as they flow to the ocean. As a consequence, many species can shift their longitudinal (elevational) distributions to match temperature conditions, as long as there are no barriers to movement.

Average precipitation along the equator in Africa is projected to remain the same; however, both drier and wetter conditions are projected to occur away from the equator (IMAGE projections). Parts of the Sahel, for example, are projected to be much wetter, whereas parts of the horn of Africa will be much drier. Stream flows and habitat will expand or contract accordingly. Although many aquatic invertebrates and fish in savanna rivers have adaptations for dealing with high temperatures, low dissolved oxygen, and desiccation, even these capacities may be exceeded if the extent and duration of desiccation is extensive (Cooper 1996).

In the monsoonal savanna systems of East Africa, seasonal and interannual variation in precipitation is likely to increase. As a consequence, streams and rivers may be subjected to an increased frequency and intensity of hydrological disturbance (i.e., droughts, floods). Species richness and biomass of fish assemblages are often directly proportional to discharge levels and/or the extent of floodplain (where present) inundation (Welcomme 1976, 1979, 1985; Welcomme and de Merona 1988). As a consequence, increased periods of desiccation would probably reduce the species diversity of fish assemblages, and possibly eliminate species that cannot withstand desiccation (Welcomme 1985). In addition, increases in the intensity and frequency of flooding may decrease fish populations in headwater areas, but increase the population sizes of fish using floodplain habitats in downstream areas (van Someren 1952; Welcomme 1985).

These projected changes in climatic conditions, however, are completely dwarfed by predicted changes in land-use patterns that ultimately result from human population growth. Human population growth rates in Africa are among the highest in the world, placing increasing demands and stresses on natural resources. African savannas are projected to be either eliminated or reduced to 16% of their present extent in the next 100 years (IMAGE projections A1 or A2). This level of habitat alteration implies the wholesale drainage of wetlands and floodplains, with the attendant loss of species that use these habitats, including resident fish species that live on floodplains and migratory fish species that use floodplains as spawning and nursery habitat. Because cropland development in semi-arid regions implies the attendant development of water resources, it is probable that levels of dam construction, groundwater pumping, and water diversions will also increase, resulting in further losses of species as habitat, resources, and migratory corridors are lost. In short, the extent of projected land-use changes and associated water development forecasts severe, widespread reductions in native species diversity in the rivers of the African savanna.

Tropical Islands

Faunal assemblages in streams on tropical islands are low in richness and dominated by insects, decapods, snails, and gobiod fish. With insects reach-
The phenomenon known as "Temperate Zones" is a significant aspect of Earth's climate and geography. These zones are characterized by a distinct seasonal cycle, with moderate temperatures throughout the year. The term "Temperate" refers to the moderate climate conditions that prevail in these regions, typically defined as areas that experience a wide range of temperatures, with neither extremely hot summers nor extremely cold winters.

Temperate Zones are found roughly between the Tropics of Cancer and Capricorn, at approximately 30° latitude north and south of the equator. This region encompasses a portion of both the Northern and Southern Hemispheres and includes a variety of ecosystems, from deciduous forests to grasslands and savannas.

The climate in these zones is marked by distinct seasons, with well-defined summer and winter months. This seasonal variation leads to a wide range of natural phenomena, including the growth cycles of plants and animals, which are strongly influenced by temperature and rainfall patterns.

In terms of human habitation, Temperate Zones have been historically significant for agriculture and settlement. The moderate climate supports a diverse range of crops and allows for year-round food production, making these regions attractive for human habitation and economic development.

Agriculture in Temperate Zones is highly productive, with a wide variety of crops that can be grown in different seasons. This includes cereals, fruits, vegetables, and livestock, which are staples in many local diets. The temperate climate also supports the growth of forests, which are critical for timber production, biodiversity, and ecosystem services.

Overall, the characteristics of Temperate Zones highlight the importance of understanding the factors that influence the climate and ecosystems in these regions. This knowledge is crucial for sustainable development, conservation efforts, and managing environmental changes that may arise due to climate shifts or human activities.

In conclusion, Temperate Zones play a vital role in the global ecological system, offering a unique blend of natural and agricultural resources that are valuable to both local communities and the broader world.
water. For example, a comparison of the historical and current distributions of Virginia fishes showed that species with small geographic ranges or narrow habitat or food requirements were especially prone to extinction (Angermeier 1995). These and other species traits are reasonably well known for many fish in the North American Temperate Deciduous Forest, and they can be used to assess the proportion of the fish fauna vulnerable to projected changes in climate and land or water use.

We identified five traits that will probably affect the sensitivity of fish species to climate change: geographic range, age at first reproduction, number of stream sizes inhabited, number of food types eaten, and flow requirements. Geographic range, which is inversely related to extinction risk (Gaston and Blackburn 1996), was estimated for all 532 fish species in the biome using Pusey and Pug (1991). The total area represented by the range map for each species was determined relative to a standard areal unit of 250,000 km². The latter four traits were examined for species native to Wisconsin or Virginia, which represent northern and southern regions of the biome, respectively. These four traits were assigned to species using Becker (1983) for Wisconsin fishes and Jenkins and Burkhead (1994) for Virginia fishes. Age at first reproduction (which is correlated with body size) is presumably directly related to extinction risk, based on previous observations that long-lived species are the first species to become extinct in chronically stressed ecosystems (Rapport et al. 1985). Large fish are generally more mobile, and they may be more effective colonizers. Specialization on a particular waterbody size or food predisposes species to extinction, especially in variable environments. We recognized three waterbody sizes (small, medium, large) and four general food types (detritus, vegetation, invertebrates, fish). Species that require flowing water are more vulnerable to extinction than those that can live in either flowing or standing water.

Many Temperate Deciduous Forest fishes are vulnerable to climate change due to their small geographic ranges. For example, 47% of the 532 species occurring in the biome have ranges of less than 100,000 km², and 19% have ranges of less than 20,000 km² (an area ca. 140 km on a side). Range sizes vary substantially among families. Over one third of the 143 darter species have ranges of less than 20,000 km², whereas most suckers and sunfishes (35 and 28 total species, respectively) have ranges greater than 600,000 km². Species with small geographic ranges are also likely to have limited dispersal abilities.

Most fishes have ecological traits that make them vulnerable to climate change. For example, 74 and 65% of the fish species in Wisconsin and Virginia, respectively, eat only one type of food (Table 14.1). The sensitivity of the fish fauna to environmental change, however, varies among regions. The proportion of fishes that require flowing water is much greater in Virginia than in Wisconsin (68% versus 27%), indicating that Virginia fishes have more climate-sensitive traits than Wisconsin fishes (medians = 2 vs. 1; Table 14.2). Sensitivity also varies among families: Many minnows and sunfishes lack sensitive traits, whereas lampreys and darters often have three or four. Given that the center of fish diversity in North America is in southern Appalachia, the sensitivity of the fauna to climate change for the entire biome is better represented by Virginia fishes than by Wisconsin fishes.

Sensitivity to environmental change and range size are interrelated. For the 197 native Virginia fishes, cumulative ecological sensitivity (indicated by the number of individual traits tallied in Table 14.2) is inversely related to range size (Kendall's tau = 0.38; p < 0.0001). In other words, ecologically sensitive fishes also tend to have small ranges. These patterns in sensitivity to environmental change are more obvious in some families than others. For example, the range of ecological sensitivity for Virginia minnows (63 species) is similar to those for all Virginia species combined, but Virginia darters (42 species) are uniformly small, ecologically specialized, and narrowly distributed; thus, they are uniformly vulnerable to environmental change.

Overall losses of fish species from the Temperate Deciduous Forest due to climate and land-use changes cannot be predicted precisely. A substantial proportion of the fish species (25–50%) appear to be acutely sensitive to projected environmental effects of climate and land use changes, based on their range sizes and ecological traits. Some groups (e.g., darters) are especially sensitive, whereas others (e.g., sunfishes) are probably relatively tolerant of such effects. Climate change itself is unlikely to cause complete elimination of many species from the Temperate Deciduous Forest; however, many

| Table 14.1. Proportion of native fish species in Wisconsin (WI) and Virginia (VA) that use a single waterbody size (NWS) or food type (NFT), require flowing water (FLO), or take more than 2 years to mature (AGE) |
|-------|-------|-------|-------|-------|
| NWS  | NFT  | FLO   | AGE   |
| WI   | 0.19  | 0.74  | 0.27  | 0.33  |
| VA   | 0.30  | 0.65  | 0.68  | 0.22  |

Proportions are based on 146 species in Wisconsin and 197 species in Virginia.

| Table 14.2. Proportions of native fish species in Wisconsin (WI) and Virginia (VA) that have 0, 1, 2, 3, or 4 ecological traits likely to result in sensitivity to global warming |
|-------|-------|-------|-------|-------|
|       | 0     | 1     | 2     | 3     | 4     |
| WI    | 0.12  | 0.43  | 0.34  | 0.09  | 0.02  |
| VA    | 0.09  | 0.25  | 0.42  | 0.23  | 0.02  |

The four traits analyzed are given in Table 14.1. Proportions are based on 146 species in Wisconsin and 197 species in Virginia.
The distribution and abundance of species across different latitudes are influenced by a variety of factors, including temperature and latitude. These factors can have a significant impact on the distribution and abundance of species, as well as on the ecosystem as a whole. This can result in the formation of distinct biogeographic regions, each with its own unique set of species and communities.

### Biogeographic Regions

- **Deserts:** These regions are characterized by low rainfall and high temperatures, resulting in a sparse vegetation and a variety of unique plant and animal species.
- **Tropical Rainforests:** These regions are characterized by high rainfall and temperatures, resulting in a dense and diverse vegetation.
- **Tundra:** These regions are characterized by cold temperatures and low rainfall, resulting in a sparse vegetation and a variety of unique plant and animal species.
- **Temperate Forests:** These regions are characterized by moderate temperatures and rainfall, resulting in a diverse and abundant vegetation.

These biogeographic regions serve as important pathways for the exchange of species and genetic material, and they play a crucial role in maintaining biodiversity and ecological balance.
likely be strongest for sensitive species that occupy unique habitats such as springs or coolwater streams. In contrast, other plains fishes would be most affected by strong increases in flow variation or marked changes in the seasonality of floods or droughts, via effects on reproductive success and the survival of larval fish. Reduced flow may also reduce water quality in reaches receiving waste effluent.

Perhaps the most pervasive effects, however, would be increased fragmentation of habitats through further irrigation diversions or increased intermittency because these would reduce the ability of fish populations to withstand harsh periods in refugium habitats and later recolonize rewetted reaches. On a regional and global scale, the effects of a warming climate would be most severe in basins where drainages tend east to west, rather than in north–south drainages that allow colonization of newly created habitats at higher latitudes. This process would have effects similar to Pleistocene glaciation, when a colder climate extirpated fish in east–west drainages (e.g., the intermountain basins of the western United States and eastern Europe), but not north–south drainages (e.g., the Mississippi Basin) (Briggs 1986).

Invasions of nonnative fish species to plains stream systems have been rare, except in reservoirs and stream reaches immediately downstream where temperatures have become cooler, flows more stable, and water less turbid (Cross and Moss 1987). Thus, if more reservoirs are built to store water as the climate warms and dries in certain regions, native species could also be reduced or extirpated, either because habitat becomes unsuitable, nonnative species exclude them, or both. Relatively few large migratory fish species inhabit plains streams, but these would be strongly affected by dispersal barriers (e.g., dams).

Projections from the IMAGE scenario A1, which incorporate the largest population increases and energy use, indicate that although the area of grassland/steppe ecosystem will decline only 12% worldwide from 1990 to 2100, much larger increases and decreases of more than 50% will occur in 7 of 11 grassland/steppe regions. This suggests that distributions of aquatic biota will need to expand and contract rapidly to adapt to the changing landscape. As climate and land use change in plains ecosystems, therefore, it will be important to maintain the dispersal routes and the integrity of unique aquatic habitats if we want to maintain the diversity of fish biota. This likely holds true for other regions, and other aquatic biota as well, because of similar life history adaptations to harsh environments.

**Cold Regions**

**Temperate Montane**

The biota of montane streams is characterized by low diversity and dominance by species requiring cold water (Ward 1994). Only a few families of fishes are represented in temperate montane streams globally. The lower elevational limits of coldwater fishes are closely associated with a critical maximum water temperature (Fausch et al. 1994; Rahel et al. 1996). These systems generally experience a large pulse of meltwater in the spring, and discharge typically drops to low levels during fall and winter (Poff and Ward 1989). Extended periods of ice cover often limit available habitat for fish (Swanston 1991), and the development of frazil or anchor ice increases winter mortality (Reiser and Wescue 1975; Brown et al. 1993).

Climate change is likely to alter both the thermal and hydrological regimes of montane streams. Montane streams near the tops of very high mountains may exhibit decreases in stream temperature due to increased snowpacks in winter and decreased solar radiation in summer (Williams et al. 1996). Very few aquatic species, however, currently reside in these harsh environments.

Of greater concern are streams at middle to lower elevations within the montane zone, including those streams that do not drain very high mountains. Here, both increased water temperature and altered flow regimes have been predicted. Because of their requirements for cold water, montane species are vulnerable to increased maximum temperatures. In North America, summer water temperatures in coldwater streams have been projected to increase by up to 2°C (Eaton and Scheller 1996).

Increases in water temperature are expected to reduce habitat availability and further restrict montane fishes to even higher elevations. In the United States, climate-change studies predict habitat loss for trout in the Rocky Mountains (Keleher and Rahel 1996; Rahel et al. 1996), for various coldwater species in the upper American Midwest (Eaton and Scheller 1996), and for brook trout in the Appalachian Mountains (Meisner 1990). In northern Europe, climate change is predicted to cause a contraction in the geographic ranges of 11 fish species and expansion in the geographic ranges of 16 fish species (Lehtonen 1996). In the Japanese archipelago, the geographic ranges of coldwater species are predicted to shrink substantially (Nakano et al. 1996). In New Zealand, nonnative brown and rainbow trout are predicted to be eliminated from warmer, northern latitudes as mean annual temperatures increase by 3°C (Scott and Poynter 1991).

Species diversity may actually increase in montane streams that undergo warming as fishes from lower elevations find thermal conditions more favorable (Baltz et al. 1982; Lehtonen 1996). Some species of trout and sculpins may be displaced by warm-water species that are introduced or invade upstream sections that become warmer (Larson and Moore 1985; Williams et al. 1989; De Staso and Rahel 1994; Thompson and Rahel 1996). Several subspecies of native trout are also subject to displacement by nonnative salmonids that can tolerate warmer temperatures (e.g., Behnke 1992; Thompson and Rahel 1996). Further, the very steep gradients typifying the uppermost reaches of montane streams can inhibit the dispersal of native coldwater species (Fausch 1989; Kruse et al. 1997), preventing an upstream retreat from nonnative competitors.

Little is known about how alterations in stream discharge might affect montane fish populations. A common projected scenario for flow regimes
In response to climate change, increased temperatures and drought stress were found to result in a

Chlorine changes in northern high-latitude regions are likely to result in a

In the general period

The loss ofcodominance (many) (from coastal temperate polders)

Observed positive and negative correlations in temperature changes in the Arctic. In 1991, the

Figure 1: Distribution of freshwater, saltwater, and terrestrial systems (from coastal temperate polders)

The loss ofcodominance (many) (from coastal temperate polders)

Observed positive and negative correlations in temperature changes in the Arctic. In 1991, the

Figure 1: Distribution of freshwater, saltwater, and terrestrial systems (from coastal temperate polders)

The loss of codominance (many) (from coastal temperate polders)
Such species could invade thermally suitable habitats provided there are no barriers to colonization.

It is likely that average air temperatures in northern Alaska are only slightly colder than the lower limits for some temperate coolwater species [e.g., rainbow trout and smallmouth bass (*Micropterus dolomieu*)]. Projections of climate warming for interior Alaska indicate that these lower limits will be reached within 100 years or less. As a consequence, Alaska will be less of a refuge for fish species specialized for extremely cold conditions. New, coolwater species will likely reach Alaska, either by long-distance migrations from marine sources or through introductions from temperate regions of North America. Present-day distributions of freshwater fishes in Alaska have been compared with redistributions expected to occur under a 4–8°C warming scenario. Western and northern coastal areas could host several Alaskan species not presently there, especially species with migratory marine life stages such as sturgeon, lamprey, and salmonids, with the latter group including brook trout (*Salvelinus fontinalis*), cutthroat trout (*O. clarki*), and rainbow trout.

Low temperatures at high latitudes limit population densities of humans (as well as other organisms), in turn limiting the ecological footprint of humans in the vast area of Alaska. Most of the landscape effects of humans that so plague the running waters of other regions (e.g., urbanization, agriculture, livestock grazing, mining, impoundments) are of very limited and localized importance in Alaska. Ecological constraints on economic development at high latitudes seem likely to continue to limit these impacts over the near future. Exploitation of natural resources (e.g., oil, timber, fisheries) as well as tourism fuels much of the Alaskan economy. Expansion of oil development has potential impacts on migratory waterfowl and mammals (both terrestrial and marine), but seems unlikely to substantially impact fresh waters. In contrast, timber harvest has had substantial effects on the streams and anadromous fishes of southeast Alaska (Murphy et al. 1997). There are plans to increase timber harvest in the boreal forest of interior Alaska. The extent to which the lessons learned from southeast Alaska (e.g., the value of riparian buffer strips, the central role of woody debris in streams, and the importance of logging roads in supply of sediments to streams) can be applied to the permafrost-riddled landscapes and low biotic productivity of the taiga is unclear.

**Quantitative Examples**

Although the magnitude of population and species losses cannot currently be quantified at the scale of a biome or climatic region, current relationships between diversity and habitat area can be used to estimate species loss under given scenarios of climate or land-use change that alter habitat area. We use data for Australian fishes to illustrate this quantitative approach. Figure 14.2 shows how fish species diversity in three groups of rivers in Australia increase as the size of the catchment increases. One group of rivers is in tropical northern Australia (predominantly Queensland), whereas the other two groups are temperate rivers in southern mainland Australia, including coastal Victorian rivers and inland rivers that flow into the Murray-Darling River system. Despite the fact that many of these rivers have been extensively damaged by land-use practices in their catchments, by the construction of barriers, and by changes in the flow regime, the graphs reveal a strong relationship between richness and catchment size and, presumably, habitat quantity. Because count data for species richness against area usually follow a Poisson rather than a normal distribution, we used Poisson regression (e.g., Dobson 1990; kindly carried out by R. MacNally) to generate a best fit model for each of the three regions. The slopes of the Poisson regressions (Fig. 14.2) indicate the rate at which species are added to streams in the three regions as a function of catchment size. Tropical streams add species faster than temperate coastal streams, which add species faster than temperate inland streams. This pattern reveals an underlying gradient in annual precipitation, with tropical streams receiv-
the basin. In the future, more detailed projections of altered precipitation in the basin will allow us to predict any species responses across stream systems. Changes do not show up to date large areas associated to the two major Provinces. The rainfall pattern in North America ranges from dry to wet. The Mississippi River basin covers a large area including many states and provinces, which are described in this section. The interactions between streams and rivers are complex and can lead to significant changes in species distribution and diversity. More precise data are needed to better understand the impact of altered precipitation on species diversity. Recent studies have shown that changes in climate are affecting species distribution and abundance across different regions. The two main factors that influence species distribution are temperature and precipitation. In this section, we will focus on the changes in temperature and precipitation in the Mississippi River basin. Temperature and precipitation data from different sources have been used to create maps showing the changes in temperature and precipitation over the years. These maps can help us understand how species distributions are changing and how these changes might affect the ecosystem. The Mississippi River basin includes a large area of wetlands, which are also important for many species. Changes in the hydrology of these wetlands can have significant impacts on species distribution and abundance. In conclusion, altered precipitation and temperature in the Mississippi River basin are expected to have significant impacts on species diversity and distribution. More research is needed to better understand these changes and their implications for biodiversity.
across this region could allow predictions of species losses, using an approach similar to that described earlier for Australian streams.

Prospectus

We are confident qualitatively that global climate and land-use changes will cause the extinctions of some fish and other riverine species. Changes in regional templates induced by climate and land-use changes will affect species in each of the climatic regions and biomes considered here. Modifications of thermal regimes, hydrologic regimes, and patterns of floodplain inundation will certainly reduce fluvial habitat and, hence, species diversity.

The relative contributions of hydrologic, temperature, and temperature changes to future declines in fish diversity appear to vary along the two major gradients we considered in this chapter: temperature and precipitation. When streams and rivers are arrayed from tropical to polar regions (thermal gradient), the importance of land use appears to decrease, primarily because most developing countries, with few land-use controls and high human population growth rates, are found in the tropics, and these countries have much greater potential for far-reaching land-use changes. By contrast, the relative importance of temperature change increases with increasing altitude or latitude (concordant with temperature-change projections). Of course, land-use changes can also be important in the temperate areas (e.g., logging in montane and boreal forests). The importance of hydrologic changes is evident along precipitation gradients, irrespective of latitude. In both tropical and temperate zones and regions appear to be more sensitive to reductions in precipitation and runoff than do the wetter regions. The ultimate impact of altered hydrologic regimes will, of course, also depend on associated land-use change.

As climate and land-use changes progress over the coming years on local, regional, and global scales, aquatic habitat will become increasingly fragmented and isolated. Much of the reduction in aquatic species diversity is already occurring, as contemporary land- and water-use practices alter the riverine landscape by modifying physical, chemical, and biological conditions, and as water resources management creates barriers to species movement through river corridors. Species that are unable to move along river corridors to find suitable environmental conditions are under increasing threat of local extinction. We expect many regional extinctions of entire species to result from the cumulative losses of isolated and stressed populations. As indicated by our analyses, these losses will be particularly important to species that have small geographic range, ecological specialization, and migratory behavior—characteristics possessed by a significant fraction of existing species. Preventing further loss of sensitive fish (and other aquatic) species, therefore, requires managers to view streams and rivers as entire river basins, in and through which aquatic species are able to move to suitable local habitats (refugia) as regional environmental conditions change.

References


