Page et al
1997

CONSERVATION IN HIGHLY FRAGMENTED LANDSCAPES

EDITED BY

MARK W. SCHWARTZ

Ecology

Conservation in Highly Fragmented Landscapes

Bringing together the writings of a diverse group of researchers and conservation planners, this invaluable text explores the critical issues related to developing an integrated conservation program within the context of severe habitat loss. Using the midwestern United States as a case study, it addresses theoretical issues related to conservation as well as practical applications of conservation-research information into reserve-system planning.

Conservation in Highly Fragmented Landscapes:

- integrates science and policy in conservation
- proposes conservation strategies for regions in which habitat loss precludes a comprehensive conservation of all native biodiversity
- specifically addresses trade-offs in conservation actions
- links basic research with practical applications
- targets issues underrepresented in the conservation literature

While presenting an integrated conservation program, this work looks at both the societal values scientists have to consider and the perceived costs imposed by conservation activities, providing professionals with specific strategies for conservation in a human-dominated landscape. The insights presented in this book will be of particular interest to applied ecologists; university, state, and conservation-organization researchers; land managers; and conservation planners.

About the editor

Mark W. Schwartz is a Plant Conservation Ecologist in the Center for Population Biology at the University of California, Davis, California.

Chapman & Hall
115 Fifth Avenue
New York, NY 10003

2-6 Boundary Row
London SE1 8HN

Printed in U.S.A.

ISBN 0-412-07031-6
90000
9 780412 070310

Cover design: Saïd Sayrafiezadeh, *Emdash Inc.*

Photo credit: Michael Jeffords (Illinois Natural History Survey)

Printed in the United States of America

Chapman & Hall
115 Fifth Avenue
New York, NY 10003

Chapman & Hall
2-6 Boundary Row
London SE1 8HN
England

Thomas Nelson Australia
102 Dodds Street
South Melbourne, 3205
Victoria, Australia

Chapman & Hall GmbH
Postfach 100 263
D-69442 Weinheim
Germany

International Thomson Editores
Campos Eliseos 385, Piso 7
Col. Polanco
11560 Mexico D.F
Mexico

International Thomson Publishing–Japan
Hirakawacho-cho Kyowa Building, 3F
1-2-1 Hirakawacho-cho
Chiyoda-ku, 102 Tokyo
Japan

International Thomson Publishing Asia
221 Henderson Road #05-10
Henderson Building
Singapore 0315

1 2 3 4 5 6 7 8 9 10 XXX 01 00 99 98 97

Library of Congress Cataloging-in-Publication Data

Conservation in highly fragmented landscapes / Mark W. Schwartz, editor.
p. cm.
Includes bibliographical references and index.
ISBN 0-412-07031-6
(pbk. : alk. paper)
1. Nature conservation–Middle West. 2. Fragmented landscapes–Middle West. 3. Natural areas–Middle West. I. Schwartz, Mark W.
QH76.5.M53C66 1997
333.95'16'0977–dc20 96-36445
CIP

British Library Cataloguing in Publication Data available

To order this or any other Chapman & Hall book, please contact **International Thomson Publishing, 7625 Empire Drive, Florence, KY 41042.** Phone: (606) 525-6600 or 1-800-842-3636. Fax: (606) 525-7778. e-mail: order@chaphall.com.

For a complete listing of Chapman & Hall titles, send your request to **Chapman & Hall, Dept. BC, 115 Fifth Avenue, New York, NY 10003.**

9

Impacts of Fragmentation on Midwestern Aquatic Organisms

Lawrence M. Page, Mark Pyron, and Kevin S. Cummings
Illinois Natural History Survey, 607 E. Peabody Dr., Champaign, IL 61820

Introduction

Fragmentation has been identified as a major cause of declines in species diversity for many terrestrial ecosystems (reviewed by Saunders 1991). Much less empirical information is available on the effects of fragmentation on freshwater species and communities (Bradford et al. 1993, Townsend and Crowl 1991). Fragmentation in streams (i.e., a lack of connectivity between upstream and downstream populations) can be caused by many anthropogenic influences, but few studies have investigated the problem. In this review we present evidence that freshwater organisms are declining as a result of factors that lead, initially, to fragmentation and, ultimately, to extirpation of populations. Examples of stream modifications that cause fragmentation are described, followed by examples of management and restoration strategies that can mitigate the impact of fragmentation.

Diversity of Stream Organisms in the Midwest

The United States has the most diverse temperate-stream biota in the world. Fishes, mussels, and crayfishes, the organisms for which the most complete information is available, are all more diverse in the United States than they are in the temperate regions of Europe or Australia (Table 9.1). Within the United States, the greatest diversity in these groups is found in streams in the southern Appalachians. Although biological diversity in the Midwest is less than in montane areas, it is greater than in most temperate regions of the world. For example, Illinois has or had 188 native species of fishes, 79 native mussels, and 20 native crayfishes.

Declines in Stream Biodiversity

Recent declines in populations of stream-inhabiting species in the Midwest are well known and well documented. The best data are for Illinois, where two statewide surveys have been conducted on fishes (Forbes and Richardson 1908,

Table 9.1. Numbers of species in temperate regions of the world. From Bogan (1993), Hobbs (1988), Merrick and Schmida (1993), Page and Burr (1991), Smith (1992), Taylor et al. (1996), Williams et al. (1993).

	Fishes	Mussels	Crayfishes
United States	800	281	308
Europe	357	16	7
Australia	185	17	102

Smith 1979), one has been completed for crayfishes (Page 1985a), and one is nearing completion for mussels (Cummings in prep.). At the turn of the century, Forbes and Richardson (1908) found 187 native species of fishes reproducing in Illinois. When Smith completed his resurvey, only 179 native fishes were still reproducing in Illinois: 8 species (4% of the total) had been eliminated in the 70 years since the original survey (Smith 1979). Today, only 17 years after the publication of Smith's study, only 175 native fishes remain. Another 4 species have disappeared, for a total loss of 6% of the native fishes (Table 9.2). The factors that contributed to the loss of fishes continue to impact streams, and 23 more species (12%) of fishes are listed as endangered or threatened in Illinois (Illinois Endangered Species Protection Board, 1994).

The loss of mussels in Illinois has been even more dramatic. Of the 79 species for which historical records are available, 17 (22%) are extirpated, and another 24 (30%) are listed as endangered or threatened (Table 9.3) (Cummings and Mayer 1997). An astonishing 52% of the native species are gone or in imminent danger of disappearing. Of the 20 species of crayfishes native to Illinois, 1 *(Cambarus robustus)* is gone (5%), and 4 (20%) are listed as endangered or threatened.

The number of extirpated and endangered species appears enormous until it is compared to the loss of native landscape. It is estimated that less than 1% of the original landscape of Illinois remains in a natural state, as defined by criteria established for an inventory of Illinois natural areas (White 1978). As discussed elsewhere in this book, the landscape of Illinois and much of the Midwest has been transformed from predominantly prairie, savanna, wetlands, and forest, to mainly corn fields, soybean fields, and urban areas.

Table 9.2. Extirpated species of native Illinois fishes.

Species lost by 1979	*Additional species lost by 1996*
Ohio lamprey, *Ichthyomyzon bdellium*	Alligator gar, *Atractosteus spatula*
Blackfin cisco, *Coregonus nigripinnis*	Bigeye chub, *Hybopsis amblops*
Muskellunge, *Esox masquinongy*	Bluehead shiner, *Pteronotropis hubbsi*
Rosefin shiner, *Lythrurus ardens*	Northern madtom, *Noturus stigmosus*
Gilt darter, *Percina evides*	
Saddleback darter, *Percina ouachitae*	
Crystal darter, *Crystallaria asprella*	
Spoonhead sculpin, *Cottus ricei*	

Table 9.3. Extinct and extirpated species of native Illinois mussels (Unionidae).

Globally Extinct	
Epioblasma flexuosa (Rafinesque, 1820)	Leafshell
Epioblasma personata (Say, 1829)	Combshell
Epioblasma phillipsii (Conrad, 1835)	Conrad's riffleshell
Epioblasma propinqua (Lea 1857)	Tennessee riffleshell
Epioblasma sampsonii (Lea, 1861)	Wabash riffleshell
Epioblasma torulosa (Rafinesque, 1820)	Tubercled blossom
Extirpated from Illinois	
Fusconaia subrotunda (Lea, 1831)	Longsolid
Hemistena lata (Rafinesque, 1820)	Cracking pearlymussel
Plethobasus cicatricosus (Say, 1829)	White wartyback
Pleurobema plenum (Lea, 1840)	Rough pigtoe
Quadrula fragosa (Conrad, 1835)	Winged mapleleaf
Epioblasma obliquata (Rafinesque, 1820)	White catspaw
Epioblasma rangiana (Lea, 1838)	Northern riffleshell
Lampsilis abrupta (Say, 1831)	Pink mucket
Leptodea leptodon (Rafinesque, 1820)	Scaleshell
Obovaria retusa (Lamarck, 1819)	Ring pink
Villosa fabalis (Lea, 1831)	Rayed bean

With the pervasive transformation that has occurred in the landscape of the Midwest, it is surprising that not more species have disappeared. Why does Illinois still have most of the native aquatic species (>90% of the fishes and crayfishes, and nearly 80% of the mussels) if most of the original landscape has been modified? The percentage of extirpated species is small in relation to the pervasiveness of the landscape modifications because species presence is determined on a statewide basis, and many species survive in the state in very small populations. The larger the area under consideration, the greater is the likelihood that at least one population will be found. When we examine data on extirpation for smaller areas, we expect to find, on average, a larger loss of species than we find when we consider an area as large as Illinois. For example, the Embarras River drainage in east-central Illinois historically supported 43 species of freshwater mussels, but only 31 (72%) are extant. In the Saline River system in southeastern Illinois, only 39 of the 67 fishes (58%) known historically in the now badly polluted river system are still present.

The relatively low number of aquatic species extirpations for the entire state is misleading as an indicator of environmental condition. Many species persist in small populations that are widely separated from all other conspecific populations and, hence, are extremely vulnerable to extirpation. The diminution and isolation of populations caused by fragmentation of the landscape and concomitant loss of suitable habitats will likely lead to a dramatic increase in the number of extirpated species in the near future in Illinois. The 23 species of fishes (13% of the surviving native species), 24 species of mussels (39% of survivors), and

4 species of crayfishes (20% of survivors) that are listed as endangered or threatened are especially vulnerable.

The deleterious effect of fragmentation on aquatic organisms is demonstrated by the temporal distributions of Illinois minnows. Forbes and Richardson (1908) found the bigeye chub *(Hybopsis amblops)* to be common in eastern Illinois in the late 1800s. Populations of the bigeye chub disappeared in subsequent decades as land use changed and by the 1950s, the species persisted only in highly fragmented populations (Fig. 9.1). By the 1960s the species was gone (Smith 1979). Causes for the extirpation of the bigeye chub were clearly understood by Smith (1979: 78), who noted that "deposits of fine silt over substrates that were once sand and gravel eliminated the habitat of the species. Other alterations of streams and their watersheds and local fish kills hastened the disappearance of this chub, and ultimately there were no sources for recruitment left." The blacknose shiner *(Notropis heterolepis)* once occurred statewide but by the middle of this century it had been reduced to a few populations in northern Illinois (Fig. 9.2). Although still extant, the blacknose shiner is affected by at least some of the same forms of degradation as was the bigeye chub, and it continues to decline in abundance.

The few remaining isolated populations of the blacknose shiner and many other aquatic species are highly vulnerable to extirpation. Prior to its isolation, a population can rebound from local extirpation through recruitment of individuals from nearby populations (Detenbeck et al. 1992). As long as environmental conditions are suitable, immigration will occur and the population will become reestablished (Bayley and Osborne 1993). For example, a population adversely affected by an extraordinary flood or drought can reconstitute in a short period of time through dispersal from other populations; in contrast, isolated or semi-isolated populations have no chance of becoming reestablished because there is no source of immigrants, or because immigration occurs too infrequently to maintain populations constantly exposed to degradation.

The impact of fragmentation may be even more detrimental to stream organisms with more complex life cycles, such as mussels, than it is to fishes. Mussels that inhabit eastern Northern America have a larva (a glochidium) that is an obligatory parasite, primarily on fishes, resulting in strong correlations between mussel and fish distributions (Watters 1992). Stream degradation can affect a mussel species directly, just as it affects a fish, or it can affect the mussel indirectly by harming or eliminating its host. Without the host to complete its life cycle, the mussel is doomed to extirpation. The large loss of mussels in the Midwest is likely due to the synergistic effects of stream degradation and loss of fish hosts (Cummings & Mayer 1992, Bogan 1993, Neves 1993, Williams et al. 1993).

The large number of populations of aquatic organisms persisting only in isolation suggests that many more will soon disappear. A mussel on the brink of extirpation in Illinois is the snuffbox *(Epioblasma triquetra)* (Fig. 9.3). Historically, the species had a statewide distribution; today, it persists only in a short as endangered or

ıs is demonstrated
Richardson (1908)
eastern Illinois in
ubsequent decades
ed only in highly
was gone (Smith
arly understood by
ubstrates that were
)ther alterations of
e disappearance of
nt left." The black-
ut by the middle of
thern Illinois (Fig.
by at least some of
continues to decline

e shiner and many
rior to its isolation,
tment of individuals
g as environmental
ılation will become
opulation adversely
te in a short period
st, isolated or semi-
ıed because there is
too infrequently to

to stream organisms
fishes. Mussels that
that is an obligatory
between mussel and
fect a mussel species
ıdirectly by harming
cycle, the mussel is
lidwest is likely due
sh hosts (Cummings
1993).
sisting only in isola-
ssel on the brink of
ı) (Fig. 9.3). Histori-
rsists only in a short

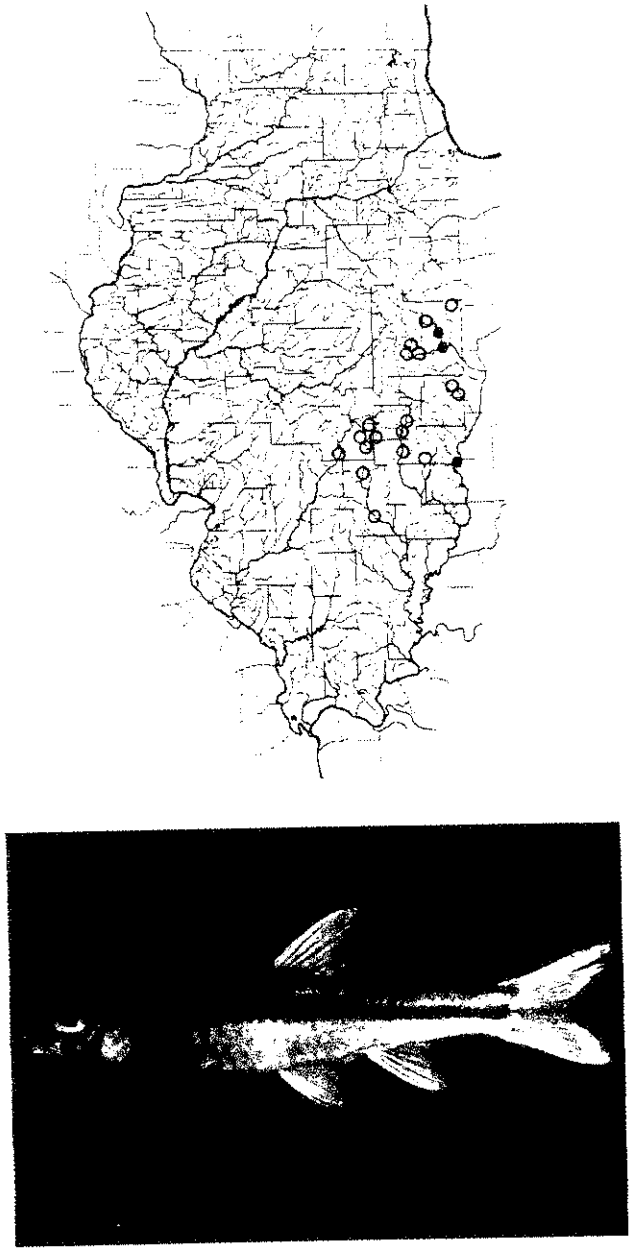

Figure 9.1. Pre-1950 (open circles) and post-1950 (black dots) distribution of the bigeye chub *(Hybopsis amblops).*

From Forbes and Richardson (1908), Smith (1979).

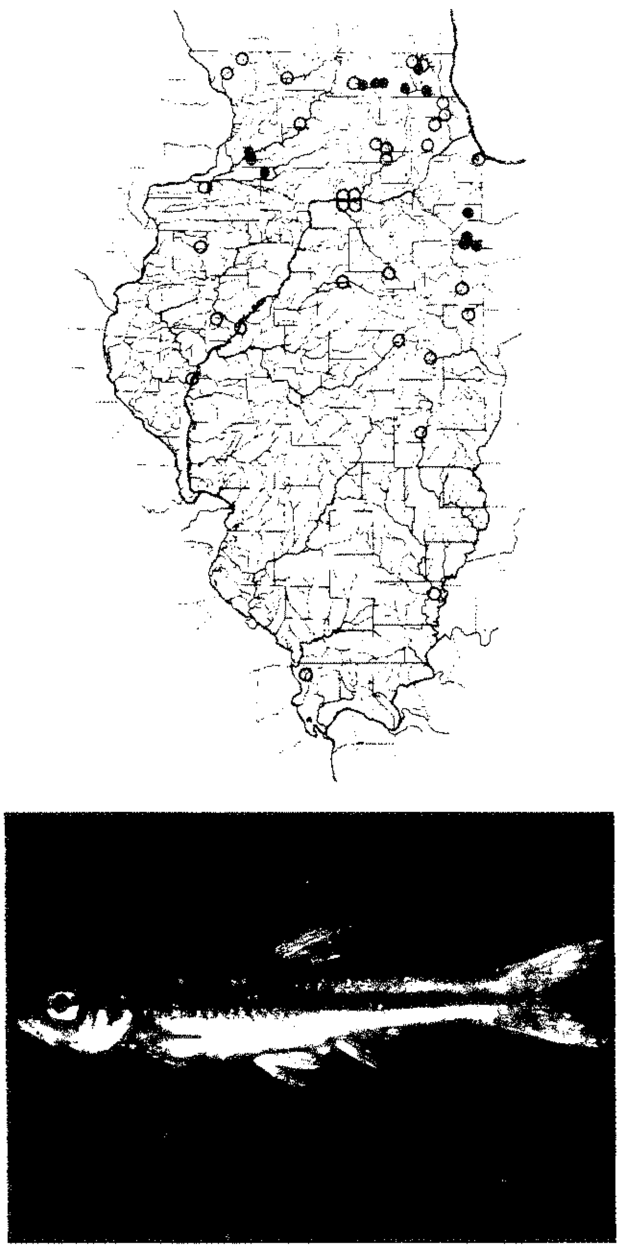

Figure 9.2. Pre-1950 (open circles) and post-1950 (blackdots) distribution of the blacknose shiner *(Notropis heterolepis)* in Illinois.

From Forbes and Richardson (1908), Smith (1979).

Figure 9.3. Pre-19
snuffbox mussel (E

Figure 9.3. Pre-1970 (open circles) and post-1970 (black dots) distribution of the snuffbox mussel *(Epioblasma triquetra).*

From Cummings (in prep.).

segment of the Embarras River. A harmful event, such as a drought or pesticide runoff, could eliminate the sole surviving Illinois population. Although the snuffbox population in Illinois is small, it appears to be self-sustaining. Other mussel species (i.e., fanshell) *(Cyprogenia stegaria)* and orange-foot pimpleback *(Plethobasus cooperianus)* are not reproducing and are likely to be extirpated from Illinois at the end of the current generation.

The above examples of the impact of fragmentation on stream organisms are midwestern, with data coming from Illinois. However, fragmentation caused by landscape modification and stream degradation is occurring throughout the United States and the rest of the developed world. Unless corrective measures are taken, the large number of species persisting only in fragmented landscapes soon will translate into an extraordinarily high number of species extinctions. Species extinctions lead to changes in food webs and other ecosystem functions which can have negative effects on other species, including those that are valuable sport and commercial species, and the process of extinction can accelerate.

Stream Habitat Fragmentation: Landscape Change and Stream Modification

Stream ecosystems are fragmented by landscape changes that render stream habitats unsuitable for aquatic organisms and by in-stream modifications that eliminate stream habitats. Smith (1971) ranked the causes of extirpation or decline in fish species in Illinois as follows: siltation (as the primary factor responsible for the loss of 2, and decimation of 14, species), drainage of bottomland lakes, swamps, and prairie marshes (0, 13), desiccation during drought (0, 12), species introductions (2, 7), pollution (2, 5), impoundments (0, 4), and increased water temperatures (0, 1). All of these factors render habitats unsuitable for many aquatic species throughout the Midwest, cause extirpations, and lead to the isolation of populations.

Other chapters in this book discuss landscape modifications that negatively affect terrestrial organisms; many of these activities also have led to major changes in stream environments. For example, streams in the Midwest naturally have wooded floodplains (Fig. 9.4) which are extremely important in maintaining a healthy aquatic environment. The vegetation on a floodplain shades the stream and prevents abnormally high water temperatures during the summer, stabilizes the stream bank and reduces erosion, and acts as a filter which removes topsoil and pesticides which would otherwise reach the stream as water drains from croplands. During periods of high water, vegetated floodplains provide feeding and spawning areas for many species of aquatic organisms and nurseries for developing larvae. When floodplains are converted to crop production (Fig. 9.5), as they have been throughout much of the Midwest, they no longer provide these benefits to aquatic organisms.

Figure 9.4.
living space
primary cau
accumulatior

The tilin
negatively i
ago (Forbe
a typical m
regular. Th
Shelbyville
and then g
of tile drair
to low stag
quickly onc
increases t
downstrear
organisms
lead to the

Siltation

Siltation, i
riparian ve

Figure 9.4. A natural stream with flowing water and a clean rocky substrate that provides living space for a great variety of species and spawning habitat for fishes. One of the primary causes of the decline in species diversity in streams in the Midwest is the accumulation of fine sediments over natural rocky substrates.

The tiling of land for agriculture is another major landscape change that has negatively impacted streams. As Forbes and Richardson noted almost 100 years ago (Forbes and Richardson 1908) in their description of the Sangamon River, a typical midwestern stream: "Formerly the flow of the river was more or less regular. This was due to the fact that the portion of the basin lying within the Shelbyville moraine was filled with swamps which absorbed the water as it fell and then gave it forth very gradually. Now, however, a very complete system of tile drainage carries off the water very quickly, and so leaves the river subject to low stages for a large part of the year." Land that once drained slowly drains quickly once it is tiled. Rapid drainage of land increases the pulse of a flood and increases the intensity and duration of low-flow once the water has moved downstream. These artificially extreme fluctuations in water levels subject stream organisms to environmental conditions to which they are not adapted and can lead to the extirpation of populations.

Siltation

Siltation, increased water temperatures, and desiccation follow the removal of riparian vegetation and the tiling of fields as land is prepared for agriculture.

Figure 9.5. Trees are being removed along this small tributary, presumably to enhance drainage of the surrounding cropland. Once the trees are removed there will be nothing to prevent topsoil and pesticides applied to the land from washing into the stream.

The excessive siltation associated with the removal of floodplain vegetation is among the most damaging forms of stream pollution in the Midwest. The clean rock and gravel substrates that normally characterize riffles and other stream habitats with fast-flowing water (Fig. 9.4) provide living space for many species of aquatic insects and other invertebrates (Hynes 1970), and important spawning habitat for many species of fishes (Balon 1975, Page 1985b). The complex nature of rocky substrates provides excellent cover from predators. This cover is important for invertebrates and small fishes that have no defense against predators other than hiding, and is important to fishes in providing places for hiding eggs. The deposition of silt covers the rocks and fills in spaces among rocks, leaving no place for small organisms to hide or to deposit their eggs.

Silt can also cover the leaves of aquatic plants and, if sufficient to prevent gas exchange or photosynthesis, will cause the plants to die. The reduction of plant life in a stream has a cascading negative impact on the stream ecosystem. Many animals, in particular insect larvae and fishes, use the plants as places to hide and forage. Some fishes use plants to hide from predators; others use plants as sites from which to ambush prey. As plants are eliminated, populations of insects and fishes are reduced or eliminated because they have fewer places to live. Fish populations are also reduced because the insects that they normally feed on are less common. Some fishes, e.g., the pugnose shiner *(Notropis anogenus)* and pugnose minnow *(Opsopoeodus emiliae)*, are particularly susceptible to the loss of plants because they are morphologically adapted to feed on insects that live on plants and are unable to survive by feeding elsewhere. These two fishes persist in the Midwest only in highly isolated populations (Smith 1979, Becker 1983).

In addition to covering the substrate, silt increases turbidity, making it more difficult for species that rely on sight to find one another for spawning, to find food, and to complete other necessary aspects of their life histories. Large-eyed fishes that rely on sight have been among those most negatively impacted. The bigeye chub *(Hybopsis amblops)* disappeared from Illinois in the 1960s; the bigeye shiner *(Notropis boops)* persists only in isolated populations (Smith 1979). The devastating effect of siltation on aquatic species results from the combination of its deposition over natural substrates and increased turbidity.

Increased Water Temperatures

The impact of increased water temperatures resulting from the loss of riparian vegetation and reduced water flow during warm seasons is difficult to separate from the effects of siltation and other factors that occur concomitantly. However, throughout the Midwest increased water temperatures per se are probably especially harmful to cool-water species such as northern pike *(Esox lucius)* and native trout *(Salvelinus* species), and species dependent on springs and spring-fed streams, such as the southern redbelly dace *(Phoxinus erythrogaster)* (Smith 1971) and many species of amphipods, isopods and crayfishes (Page 1974, 1985a).

Stream Desiccation

As discussed above, stream desiccation is thought to be primarily an effect of the artificially extreme fluctuations in water levels that follow the tiling of fields for agriculture. The rapid drainage of surrounding land increases the intensity and prolongs the duration of low-flow once the water has moved downstream. A drought that historically would have decreased the flow in a stream can now lead to a dry stream bed. During the drought of 1988, the upper 50 miles of the Sangamon River streambed were dry in late summer for a period of several weeks (Page pers. obs.); obviously this eliminated, at least temporarily, virtually all of the aquatic species that had been present. Complete drying of the upper Sangamon River may never have occurred prior to tiling of the drainage basin.

Irrigation, although not nearly as extensive in the Midwest as it is in the West (Moyle and Williams 1990), will exacerbate the problem of stream desiccation in the Midwest if it increases. As more water is removed from aquifers to supply agriculture and urban use, less will remain in streams.

Drainage of Bottomland Lakes

Floodplains of large rivers normally have low areas that fill with water during floods and survive year-round as shallow lakes. These lakes provide primary habitat for a wide variety of plants and animals. Because they naturally have luxuriant plant growth, they are important feeding areas for waterfowl, and they provide spawning areas, nurseries for larvae, and overwintering refugia for fishes.

Unfortunately, most of the bottomland lakes in the Midwest have been drained to create cropland, and those that remain have become shallow and barren because of the tremendous silt loads deposited in them each year during periods of high water. The shallow muddy lakes no longer support the plant life that was fundamental to successful completion of the life cycles of many aquatic species. Several species that persist only in isolated areas are those that depend on bottomland lakes or other vegetated bodies of standing water for their survival; e.g., spotted sunfish *(Lepomis punctatus)*, bantam sunfish *(Lepomis symmetricus)*, and the crayfish *Orconectes lancifer*.

Introduction of Non-Native Species

Several recent reviews discussed the causes of fish introductions and their impacts on biological communities (Moyle 1976, Welcomme 1988, Crowl et al. 1992). The impacts of introduced fishes identified by Moyle et al. (1986) were competition, predation, inhibition of reproduction, environmental modification, transfer of parasites and diseases, and hybridization.

Flecker and Townsend (1994) noted that introductions into communities lacking the invading guild are most likely to cause community-level effects. For example, introductions of trout, which feed heavily on insects, into North American streams where other trout occur result in population changes in native trout and other salmonids, but introductions of trout into streams lacking large insectivores are likely to result in more extensive community-level effects. Ecosystem changes from introduced species are difficult to measure; however, Moyle (1976) described several examples of a single species of fish disrupting normal ecosystem function.

In the Midwest, the most spectacular results of introduced species have been changes in the biological communities of the Great Lakes. The arrival of the sea lamprey *(Petromyzon marinus)* in the 1940s was followed by precipitous declines in, among other species, the commercially important lake trout *(Salvelinus namaycush)* and whitefishes (*Coregonus* species). Subsequent introductions, some of which were accidental, e.g., the alewife *(Alosa pseudoharengus)* and white perch *(Morone americanus)*, and some of which were deliberate, e.g., the rainbow smelt *(Osmerus mordax)* and coho salmon *(Oncorhynchus kisutch)*, have led to further declines in native species. Fishes introduced into midwestern streams have included Eurasian carps (e.g., carp *[Cyprinus carpio]* and grass carp *[Ctenopharyngodon idella]*) that are known to significantly alter aquatic communities by feeding on or uprooting plants.

Freshwater mussels and crayfishes have been seriously impacted in the Midwest in recent decades by exotic invaders, most notably the zebra mussel *(Dreissena* *polymorpha)* and the rusty crayfish *(Orconectes rusticus)*. Nalepa (1994) documented the severe decline in native mussels due to the invasion of zebra mussels in Lake St. Clair over a six-year period. He found that mussel densities declined from 2.4 m^{-2} in 1986 to 0 m^{-2} in 1992 in areas heavily infested with zebra mussels. The rusty crayfish, introduced through its use as fishing bait, is rapidly spreading through parts of the Midwest and displacing native crayfishes (Taylor and Redmer 1996).

Pollution

Neves and Angermeier (1990) cite examples of chemical spills resulting in the deaths of large numbers of fishes and invertebrates. They found that, although most fishes and invertebrates are able to recolonize because the impact is localized, mollusks have a more difficult time doing so because of their limited dispersal abilities.

Baker (1922) examined the effects of sewage and manufacturing wastes on the molluscan fauna of the Vermilion River in east-central Illinois in 1918–1920. He found that sewage pollution had killed almost all aquatic life in the Salt Fork Vermilion River for a distance of 14 miles below the city of Urbana and created unfavorable conditions for a distance of 20 miles.

Point sources of pollution include industrial wastes and domestic sewage. In the Midwest considerable progress has been made in identifying and eliminating point sources of pollution, and water quality has improved as a result (Jackson and Davis 1994). Nonpoint sources are now a larger problem than are point sources, and include siltation, as discussed above, and agricultural pesticides that reach streams following the removal of floodplain vegetation. Because of the pervasive nature of agriculture in the Midwest, some form of pollution has affected a large percentage of streams. The impact on the stream varies with the type and intensity of pollution and the tolerance of the species present.

Impoundments and River Regulation

Impounding a stream converts it into a standing body of water that lacks the riffles, runs, pools, and other habitats that stream-inhabiting organisms require. Most stream species are eliminated from the inundated area, and upstream and downstream populations become isolated from one another. There are many examples of fishes being extirpated from a stream by an impoundment, and even more examples of extirpations that have occurred as a result of multiple effects that include impoundments (Miller et al. 1989).

Freshwater mussels seem to be particularly susceptible to loss of habitat caused by the creation of impoundments (Bates 1962, Suloway et al. 1981, Williams et al. 1992, Parmalee and Hughes 1993). While some mussels may be able to survive in the lentic habitat created by an impoundment, many of these populations are functionally sterile and will eventually die out (Williams 1969). An example of the loss of mussels in an impounded stream is the fauna of the Little Tennessee

River, where only 6 of the 50 mussels once found in the river can now be found in Tellico Lake (Parmalee and Hughes 1993).

Dams also block migrations of fishes that, in many species, are necessary for reproduction (Fig. 9.6) (Holden 1979). The loss of migratory fishes from a stream ecosystem can lead to the loss of mussels using the migratory fishes as glochidial hosts and other species important to the ecosystem. Other adverse effects caused by impoundments are increased parasitism, low temperature, oxygen sags, increased water pressure, and siltation (Fuller 1974). Diverse mussel beds are often found below dams where highly oxygenated water and a stable substrate provide excellent habitat for mussels. However, dams that utilize a hypolimnetic discharge release cold, unoxygenated waters which can eliminate mussel populations for a considerable distance below the dam.

How water is released from a reservoir determines the impact on downstream habitats. The temperature and dissolved oxygen of release water depend on whether water is released from upper or lower levels behind the dam. Cold

Figure 9.6. Dams can block migrations of fishes that, in many species, are necessary for reproduction.

hypolimnial release water was identified years ago as a cause of fish extirpations (Spence and Hynes 1971). The release regime determines water levels and flow fluctuations downstream. "Flow regulation by dams disrupts the downstream river system's natural disturbance regimes" (Ward and Stanford 1995). Longitudinal and lateral connectivity that are necessary for transmission of nutrients, silt, and allochthonous materials are lost with river regulation (Welcomme 1995). The release regime also affects the channel hydrology, which impacts organisms inhabiting downstream reaches (Ward and Stanford 1995).

River regulation not only affects biota within the river but also along the entire floodplain. Riparian tree species that are closely tied to the hydrological regime do not recruit without normal flow regimes, resulting in replacement with late successional community species (Ward and Stanford 1995). Stable channel conditions resulting from river regulation are leading to a decline in prairie rivers of North America.

Most reservoirs may not be old enough to have caused genetic differentiation (although see Hansen et al. 1993), or populations might be sufficiently large above and below stream sections that are isolated by dams that genetic drift might not be apparent (Berg and Gall 1988). King et al. (1985) found genetic differences between populations of *Cyprinella lutrensis* collected at different distances from a dam on the Brazos River, Texas. The variation corresponded with differences in temperature tolerance, with one-third of the variation attributable to stream regulation effects.

Channelization

Channelization is the straightening of a stream to enhance drainage of the surrounding land. The straightening converts the diversity of habitats in a stream to one continuous straight channel (Fig. 9.7) that supports few species (Shields et al. 1995). Reduced fish numbers and biomass were found after channelization and construction of weirs in streams in Indiana (Karr and Gorman 1975).

Because of their sedentary nature mussels are particularly susceptible to the effects of channelization. In a mussel survey of the Kankakee, Yellow, and Iroquois rivers in Indiana and Illinois, Wilson and Clark (1912: 34) noted that the rivers had a "very rich and varied mussel fauna throughout their entire lengths, except in those portions which have been artificially dredged." They further stated that dredging "annihilates" the fauna and creates conditions which are unsuitable for new populations to reestablish themselves. They noted that portions of the basin that had been dredged 15–20 years ago showed no signs of recolonization even though there were many mussels in nearby tributaries.

Detection of Fragmentation Prior to Extinction

Genetic monitoring of isolated populations is necessary for conservation of fisheries (Ryman 1991) and of fishes in general (Bruton 1995), and for detection of

Figure 9.7. A channelized stream. Channelization converts the diversity of habitats in a natural stream to a continuous straight channel that supports far fewer species than were there originally.

fragmented populations. Meffe and Vrijenhoek (1988) described a model for examining the population structure of fishes that results from varying degrees of the connectivity of streams. Their model is intended to describe population structure in streams that are dewatered, resulting in reduced gene flow between isolated populations. However, it appears to be useful for detecting effects of any natural or anthropogenic causes of population fragmentation. The model generates a hierarchical population structure of genetically defined groups in isolated populations.

Shuter (1990) suggested that population monitoring of smaller fish species can provide early evidence of environmental degradation. Small fishes are usually lower in a food web, often depend on sensitive invertebrate species, and respond more rapidly to stresses (Shuter 1990). An alternative to population monitoring is the detection of fluctuating asymmetry among individuals in a population to identify environmental stress (Leary and Allendorf 1989). We suggest that in addition to genetic monitoring programs, mark-recapture studies are badly needed to understand normal movements of fishes and other aquatic organisms and, hence, the impacts of stream habitat fragmentation.

Management Strategies

Fragmentation of habitats and the resulting local extinctions have been studied extensively for certain groups of terrestrial organisms (see other chapters), but similar studies of aquatic organisms are nearly nonexistent. Little information is available on the magnitude of fragmentation in aquatic ecosystems or its impact on aquatic organisms.

Management strategies for aquatic ecosystems must consider the entire watershed. Attempting to correct problems locally, without consideration of upstream activities and downstream implications, will result in partial and probably temporary improvement at best. Management directed at improving in-stream conditions must be linked to proper management of the surrounding terrestrial landscape.

Reserves, areas where biotic communities are more or less intact and are managed to protect their natural characteristics, are mostly designed around terrestrial communities. In the Midwest, biological reserves tend to be small and rarely, if ever, protect an entire watershed. A new concept being developed in Illinois is the recognition and management of *macrosites,* areas that are large and contain the best remaining biological resources. Although use of the land for recreation, agriculture, and other consumptive activities will continue, management will strive to reverse whatever forms of degradation have affected the area. Macrosites are being selected on a watershed basis, and therefore streams included in the area will be offered protection from harmful activities.

The National Wild and Scenic Rivers Act, passed into law in 1968, recognizes that certain streams have "outstandingly remarkable" value and should be protected from development. The Act provides protection against dams and other forms of development on rivers, and also sets aside a quarter-mile riparian corridor in which development on public lands is restricted. Although affording important protection to some of the most outstanding rivers in the United States, the Act does not control watershed activities; streams federally designated as wild and scenic can still be degraded. The most important impact of the Act may be that it recognizes the inherent value of streams and provides a national policy for their protection.

Correction of some factors that have led to stream habitat fragmentation in past decades is relatively easy. Important initiatives that society has taken and seems to be in favor of continuing include building sewage treatment plants and avoiding the construction of mainstream impoundments when possible. Other initiatives, such as stopping the removal of riparian vegetation, cessation of stream channelization and dredging, and the drainage of bottomland lakes, require more public education and governmental action including, perhaps, providing better incentives to landowners. Assuming that pollution will be held at current levels or reduced, nothing will be more beneficial to the biota of midwestern streams than to have natural riparian vegetation restored. Siltation, desiccation, and elevated temperatures would all be reduced to acceptable levels if streams were lined with native plants that shaded the stream, stabilized the banks, and filtered sediment and chemicals from runoff before they reached the stream. A promising method of protecting riparian vegetation without government ownership is the establishment of conservation easements, where a private landowner or organization agrees to restrict or prohibit land uses deemed detrimental to the property's conservation value in exchange for tax relief (Roth 1994).

Most introductions of exotic fishes have been done in an effort to improve sport or commercial fishing, and usually government agencies have been responsible for the introductions. We now know that non-native species alter ecosystems, and the long-term effect of any introduction is likely to be negative rather than positive. No new introductions should be allowed in any waters. Additional legislation is needed to prevent accidental introductions from ballast water and other sources.

Restoration of Stream Habitats

Much information is now available on stream hydrodynamics, habitat preferences of aquatic species, and which habitats or stream reaches support the highest species diversity in a given region. Given the opportunity, streams will restore themselves. Often the best approach to restoration may be to encourage restoration of the native vegetation of the drainage basin, in particular the riparian zone, correct any additional pollution problems, and let the stream return to natural conditions. Over time, even channelized ditches will begin to meander (Fig. 9.8) and develop the riffle and pool habitats that are necessary for restoration of normal stream biodiversity.

A more activist approach to stream restoration, i.e., adding structures that imitate natural stream habitats, has been successful in a number of restoration projects (Newbury and Gaboury 1993). The fish and invertebrate fauna in channelized streams has been shown to be improved by the addition of weirs or structures that increase pool habitat (Borchardt 1993, Shields et al. 1995). Other recommendations for fish habitat improvements are described by Poddubny and Galat (1995), including construction of islands, diking, and restoration and preservation of preferred habitats in the main channel. Restoration of streams requires imitating the hydraulic habitat units of that geologic region to produce habitat heterogeneity of pool, riffle, and run development (Rabeni and Jacobson 1993). However, modifications for habitat improvement such as in-channel structures require knowledge of the resulting hydrological changes to the channel to avoid creating more damage (Rosgen 1994).

Restoration efforts in large river systems begin with restoring the natural flooding regime to allow connectivity between the floodplains and the river. Lands adjacent to large rivers that are not farmed on an annual basis and yet are protected from floods by federal levees should be allowed to flood. Organic matter and woody debris should be restored to provide habitat for species dependent on such materials for food and living space (Hesse and Sheets 1993).

For existing dams, management plans need to be developed that more closely

Figure 9.8. Left alone, this channelized ditch has begun to meander and develop the riffle and pool habitats that are necessary for restoration of normal stream biodiversity. If the native vegetation of the riparian zone returns and any existing pollution problems are eliminated, the stream will return to more natural conditions.

mimic natural disturbance regimes of rivers (Ward and Stanford 1995). Plans should call for releasing water that is not too cold or hot, is not anoxic, and that allows downstream flow characteristics that allow survival and reproduction of stream species. The amount, duration, and frequency of releases should mimic the original river or a nearby reference river (Gippel and Stewardson 1995). Bayley (1991) suggested that natural, predictable flood pulses result in increased fish diversity, which results in increased production and is an important step in restoring the natural hydrological regime of a river. The reestablishment of connectivity between river channels and their floodplains is becoming a recognized component of restoration (Ward and Stanford 1995). Unnecessary dams often should be removed, although care needs to be taken that the release of silt, and toxins in the silt, which have built up behind the dam is done in a way that will not damage downstream habitats.

In the Midwest, an example of a river restoration project is that on the upper Mississippi River. Theiling (1995) details current habitat rehabilitation on the upper Mississippi River which is designed to restore side channels and backwaters from sedimentation. Various techniques have been used including island construction, notching existing wing dikes, alternative bank revetments (to prevent channel movement) that create artificial backwaters, and bendway weirs that prevent deposition from filling in the main channel. Theiling (1995) suggests that these are necessary but are limited due to the small areas they affect. Infrequent, planned drawdowns to expose backwater and channel border sediments will allow vegetation to become established in wetland management areas and transform backwater and channel border habitats as they are flooded.

Additional restoration measures that have met with success include cleaning lakes and streams by limiting effluents, stopping management agencies' promotion of exotic species, and decreasing reservoir construction by examining real costs and benefits. Protection of streams at the ecosystem level by including all processes and habitats is essential to preserving the remaining aquatic biota (Franklin 1993).

Acknowledgments

We appreciate the help of Christopher A. Taylor and Donald W. Webb who read and improved the manuscript. Chris Taylor also provided information on the numbers of crayfishes in different parts of the world. Maurice Kottelat provided an estimate of the number of fishes in temperate Eurasia. Thanks to Christine A. Mayer for help in preparing the figures.

References

Baker, F.C. 1922. The molluscan fauna of the Big Vermilion River, Illinois: with special reference to its modification as the result of pollution by sewage and manufacturing wastes. *Illinois Biological Monographs* 7(2):105–224.

Balon, E.K. 1975. Reproductive guilds of fishes: a proposal and definition. *Journal of the Fisheries Research Board of Canada* 32:821–864.

Bates, J.M. 1962. The impact of impoundment on the mussel fauna of Kentucky Reservoir, Tennessee River. *American Midland Naturalist* 68(1):232–236.

Bayley, P.B. 1991. The flood pulse advantage and the restoration of river-floodplain systems. *Regulated Rivers* 6:75–86.

Bayley, P.B., and L.L. Osborne. 1993. Natural rehabilitation of stream fish populations in an Illinois catchment. *Freshwater Biology* 29:295–300.

Becker, G.C. 1983. *Fishes of Wisconsin.* University of Wisconsin Press. Madison, WI.

Berg, W.J., and G.A.E. Gall. 1988. Gene flow and genetic differentiation among California coastal rainbow trout populations. *Canadian Journal of Fisheries and Aquatic Sciences* 45:122–131.

Bogan, A.E. 1993. Freshwater bivalve extinctions *(Mollusca: Unionoida)*: a search for causes. *American Zoologist* 33:599–609.

Borchardt, D. 1993. Effects of flow and refugia on drift loss of benthic macroinvertebrates: implications for habitat restoration in lowland streams. *Freshwater Biology* 29:221–227.

Bradford, D.F., F. Tabatabai, and D.M. Graber. 1993. Isolation of remaining populations of the native frog, *Rana muscosa*, by introduced fishes in Sequoia and Kings Canyon National Parks, California. *Conservation Biology* 7:882–888.

Bruton, M.N. 1995. Have fishes had their chips?: the dilemma of threatened fishes. *Environmental Biology of Fishes* 43:1–27.

Crowl, T.A., C.A. Townsend, and A.R. McIntosh. 1992. The impact of introduced brown and rainbow trout on native fish: the case of Australasia. *Reviews in Fish Biology and Fisheries* 2:217–241.

Cummings, K.S., and C.A. Mayer. 1992. *Field Guide to Freshwater Mussels of the Midwest.* Illinois Natural History Survey Manual 5. Champaign, Ill.

Cummings, K.S., and C.A. Mayer. 1997. The status of the freshwater mussel *(Unionacea)* fauna in Illinois. In *Conservation and Management of Freshwater Mussels II: Initiatives for the Future: Proceedings of a UMRCC Symposium, 16–18 October 1995, St. Louis, Missouri.* Upper Mississippi River Conservation Committee, Rock Island, Ill.

Detenbeck, N.E., P.W. DeVore, G.J. Niemi, and A. Lima. 1992. Recovery of temperate-stream fish communities from disturbance: a review of case studies and synthesis of theory. *Environmental Management* 16:33–53.

Flecker, A.S., and C.R. Townsend. 1994. Community-wide consequences of trout introduction in New Zealand streams. *Ecological Applications* 4:798–807.

Forbes, S.A., and R.E. Richardson. 1908. *The Fishes of Illinois.* Illinois State Laboratory of Natural History. Champaign, Ill.

Franklin, J.F. 1993. Preserving biodiversity: species, ecosystems, or landscapes? *Ecological Applications* 3:202–205.

Fuller, S.L.H. 1974. Clams and mussels *(Mollusca: Bivalvia)*. In C.W. Hart, Jr. and S.L.H. Fuller eds. *Pollution Ecology of Freshwater Invertebrates.* Academic Press, New York, 215–273.

Gippel, C.J., and M.J. Stewardson. 1995. Development of an environmental flow management strategy for the Thomason River, Victoria, Australia. *Regulated Rivers* 10:121–135.

Hansen, M.M., V. Loeschcke, G. Rasmussen, and V. Simonsen. 1993. Genetic differentiation among Danish brown trout *(Salmo trutta)* populations. *Hereditas* 118:177–185.

Hesse, L.W., and W. Sheets. 1993. The Missouri River hydrosystem. *Fisheries* 18:5–14.

Hobbs, H.H., Jr. 1988. Crayfish distribution, adaptive radiation and evolution. In D.M. Holdich and R.S. Lowery eds. *Freshwater Crayfish: Biology, Management, and Exploitation.* Croom Helm, London, 52–82.

Holden, P.B. 1979. Ecology of riverine fishes in regulated stream systems with emphasis on the Colorado River. In J.V. Ward and J.A. Stanford eds. *The Ecology of Regulated Streams.* Plenum Press, New York, 57–74.

Hynes, H.B.N. 1970. *The Ecology of Running Waters.* Liverpool University Press, Liverpool.

Illinois Endangered Species Protection Board. 1994. *Checklist of Endangered and Threatened Animals and Plants of Illinois.* Illinois Endangered Species Protection Board. Springfield, Ill.

Jackson, S., and W. Davis. 1994. Meeting the goal of biological integrity in water-resource programs in U.S. Environmental Protection Agency. *Journal of the North American Benthological Society* 13:592–597.

Karr, J.R., and O.W. Gorman. 1975. Effects of land treatment on the aquatic environment. In *Non-Point Source Pollution Seminar: Section 108(a) Demonstration Projects.* U.S. Environmental Protection Agency, Office of the Great Lakes Coordinator, Chicago, Ill., EPA-905/9-75-007, 120–130.

King, T.L., E.G. Zimmerman, and T.L. Beitinger. 1985. Concordant variation in thermal tolerance and allozymes of the red shiner, *Notropis lutrensis*, inhabiting tailwater sections of the Brazos River, Texas. *Environmental Biology of Fishes* 13:49–57.

Leary, R.F., and F.W. Allendorf. 1989. Fluctuating asymmetry as an indicator of stress: implications for conservation biology. *Trends in Research in Ecology and Evolution* 4:214–217.

Meffe, G.K., and R.C. Vrijenhoek. 1988. Conservation genetics in the management of desert fishes. *Conservation Biology* 2:157–169.

Merrick, J.R. and G.E. Schmida. 1993. *Australian Freshwater Fishes.* Griffen Press Limited, Netley, South Australia.

Miller, R.R., J.D. Williams, and J.E. Williams. 1989. Extinctions of North American fishes during the past century. *Fisheries* 14:22–38.

Moyle, P.B. 1976. Fish introductions in California: history and impact on native fishes. *Biological Conservation* 9:101–118.

Moyle, P.B., H.W. Li, and B.A. Barton. 1986. The Frankenstein effect: impact of introduced fishes on native fishes in North America. In R.H. Stroud ed. *Fish Culture in Fisheries Management.* American Fisheries Society, Bethesda, Md., 415–426.

Moyle, P.B., and J.E. Williams. 1990. Biodiversity loss in the temperate zone: Decline of native fish fauna of California. *Conservation Biology* 4:275–283.

Nalepa, T.F. 1994. Decline of native unionid bivalves in Lake St. Clair after infestation by the zebra mussel, *Dreissena polymorpha. Canadian Journal of Fisheries and Aquatic Sciences* 51:2227–2233.

Neves, R.J. 1993. A state-of-the-Unionids address. In K.S. Cummings, A.C. Buchanan, and L.M. Koch eds. *Conservation and Management of Freshwater Mussels. Proceedings of a UMRCC Symposium, 12–14 October 1992, St. Louis, Missouri.* Upper Mississippi River Conservation Committee, Rock Island, Ill., 1–9.

Neves, R.J., and P.L. Angermeier. 1990. Habitat alteration and its effects on native fishes in the upper Tennessee River system, east-central U.S.A. *Journal of Fish Biology* 37(Supplement A):45–52.

Newbury, R.W., and M.N. Gaboury. 1993. *Stream Analysis and Fish Habitat Design—A Field Manual.* Newbury Hydraulics Ltd., Gibsons, British Columbia.

Page, L.M. 1974. Aquatic *Malacostraca* recorded from Illinois, with notes on their distributions and habitats within the state. *Transactions of the Illinois State Academy of Science* 67:89–104.

Page, L.M. 1985a. The crayfishes and shrimps *(Decapoda)* of Illinois. *Illinois Natural History Survey Bulletin* 33:335–448.

Page, L.M. 1
History Su
Page, L.M.,
Mifflin, Bo
Parmalee, P.
Unionidae.
River. *Ann*
Poddubny, A
effects of
Rabeni, C.F.
habitat res
Rosgen, D.L
Roth, J. 199
Ryman, N.
of Fish Bi
Saunders, D
Conservat
Shields, F.D
restoratio
Shuter, B.J.
sium 8:14
Smith, B.J.
lian Gove
Smith, P.W.
of Factor
Survey B
Smith, P.W
Spence, J.A
downstre
Sciences
Suloway, L
(Mollusc
sis on the
74(1/2):
Taylor, C.
Illinois.
cean Bi
Taylor, C.
Pflieger.
and Can
Theiling,
Rivers

gical integrity in water-resource
Journal of the North American

ient on the aquatic environment.
) Demonstration Projects. U.S.
at Lakes Coordinator, Chicago,

Concordant variation in thermal
nsis, inhabiting tailwater sections
f Fishes 13:49–57.

nmetry as an indicator of stress:
earch in Ecology and Evolution

genetics in the management of

reshwater Fishes. Griffen Press

Extinctions of North American

tory and impact on native fishes.

enstein effect: impact of introduced
roud ed. Fish Culture in Fisheries
, Md., 415–426.

ss in the temperate zone: Decline
logy 4:275–283.

in Lake St. Clair after infestation
in Journal of Fisheries and Aquatic

K.S. Cummings, A.C. Buchanan,
f Freshwater Mussels. Proceedings
Louis, Missouri. Upper Mississippi
–9.

ation and its effects on native fishes
U.S.A. Journal of Fish Biology

nalysis and Fish Habitat Design—
ns, British Columbia.

Illinois, with notes on their distribu-
f the Illinois State Academy of Sci-

capoda) of Illinois. Illinois Natural

Page, L.M. 1985b. Evolution of reproductive behaviors in percid fishes. *Illinois Natural History Survey Bulletin* 33:275–295.

Page, L.M., and B.M. Burr. 1991. *A Field Guide to Freshwater Fishes.* Houghton Mifflin, Boston.

Parmalee, P.W., and M.H. Hughes. 1993. Freshwater mussels *(Mollusca: Pelecypoda: Unionidae)* of Tellico Lake: twelve years after impoundment of the Little Tennessee River. *Annals of the Carnegie Museum* 62(1):81–93.

Poddubny, A.G., and D.L. Galat. 1995. Habitat associations of Upper Volga River fishes: effects of reservoirs. *Regulated Rivers* 11:67–84.

Rabeni, C.F., and R.B. Jacobson. 1993. The importance of fluvial hydraulics to fish-habitat restoration in low-gradient alluvial streams. *Freshwater Biology* 29:211–220.

Rosgen, D.L. 1994. A classification of natural rivers. *Catena* 22:169–199.

Roth, J. 1994. Conservation easements and their use in Illinois. *Illinois Steward* 3:3–5.

Ryman, N. 1991. Conservation genetics considerations in fishery management. *Journal of Fish Biology* 39(Supplement A):211–224.

Saunders, D.A. 1991. Biological consequences of ecosystem fragmentation: a review. *Conservation Biology* 5:18–32.

Shields, F.D., Jr., S.S. Knight, and C.M. Cooper. 1995. Incised stream physical habitat restoration with stone weirs. *Regulated Rivers* 10:181–198.

Shuter, B.J. 1990. Population-level indicators of stress. *American Fisheries Society Symposium* 8:145–166.

Smith, B.J. 1992. *Zoological Catalogue of Australia*, vol. 8. *Non-Marine Mollusca.* Australian Government Publishing Service, Canberra.

Smith, P.W. 1971. *Illinois Streams: A Classification Based on Their Fishes and an Analysis of Factors Responsible for Disappearance of Native Species.* Illinois Natural History Survey Biological Notes No. 76. Champaign, Ill.

Smith, P.W. 1979. *The Fishes of Illinois.* University of Illinois Press, Urbana.

Spence, J.A., and H.B.N. Hynes. 1971. Differences in fish populations upstream and downstream of a mainstream impoundment. *Canadian Journal of Fisheries and Aquatic Sciences* 28:45–46.

Suloway, L., J.J. Suloway, and E.E. Herricks. 1981. Changes in the freshwater mussel *(Mollusca: Pelecypoda: Unionidae)* fauna of the Kaskaskia River, Illinois, with emphasis on the effects of impoundment. *Transactions of the Illinois State Academy of Science* 74(1/2):79–90.

Taylor, C.A. and M. Redmer. 1996. The dispersal of the crayfish *Orconectes rusticus* in Illinois, with notes on species displacement and habitat preference. *Journal of Crustacean Biology* 16:547–551.

Taylor, C.A., M.L., Warren, Jr., J.F. Fitzpatrick, Jr., H.H. Hobbs III, R.F. Jezerinac, W.L. Pflieger, and H.W. Robison. 1996. Conservation status of crayfishes of the United States and Canada. *Fisheries* 21:25–38.

Theiling, C.H. 1995. Habitat rehabilitation on the upper Mississippi River. *Regulated Rivers* 11:227–238.

Townsend, C.R. and T.A. Crowl. 1991. Fragmented population structure in a native New Zealand fish: an effect of introduced trout? *Oikos* 61:347–354.

Ward, J.V., and J.A. Stanford. 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. *Regulated Rivers* 11:105–119.

Watters, G.T. 1992. Unionids, fishes, and the species area curve. *Journal of Biogeography* 19:481–490.

Welcomme, R.L. 1988. International introductions of inland aquatic species. *FAO Fisheries Technical Paper* 294:1–318.

Welcomme, R.L. 1995. Relationships between fisheries and the integrity of river systems. *Regulated Rivers* 11:121–136.

White, J. 1978. *Illinois Natural Areas Inventory Technical Report.* Illinois Natural Areas Inventory, Urbana.

Williams, J.C. 1969. *Mussel Fishery Investigations, Tennessee, Ohio, and Green rivers. Final Report.* Kentucky Department of Fish and Wildlife Resources, Frankfort, Kentucky.

Williams, J.D., S.L.H. Fuller, and R. Grace. 1992. Effects of impoundments on freshwater mussels *(Mollusca: Bivalvia: Unionidae)* in the main channel of the Black Warrior and Tombigbee rivers in western Alabama. *Bulletin of the Alabama Museum of Natural History* 13:1–10.

Williams, J.D., M.L. Warren, Jr., K.S. Cummings, J.L. Harris, and R.J. Neves. 1993. Conservation status of freshwater mussels of the United States and Canada. *Fisheries* 18:6–22.

Wilson, C.B., and H.W. Clark. 1912. The mussel fauna of the Kankakee basin. *Report and Special Papers of the U.S. Fish Commission.* [Issued separately as U.S. Bureau of Fisheries Document 758]. 1911:1–52.

10

Midwest
Natural

Mark W. Sc
Center for P
95616

Sharon M.
Tall Timbers

A mounta
"many wa
of wind, s
in the air-

Introductior

In this chapt
mented land
agencies vie
by Pyne 198
has been a s
that fire was
prescribed b
studied for i
al. 1989a,b;
1992). Mode
include disc
et al. 1980,
to indicate t
by frequent
et al. 1980, C
oak savanna
Gleason 191
Today the
and not whe
1996). With
Burn freque