Proceedings of the First Freshwater Mollusk Conservation Society Symposium, 1999, pages 261-274

# Freshwater mussels and water quality: A review of the effects of hydrologic and instream habitat alterations

G. Thomas Watters[1]

*Ohio Biological Survey and Aquatic Ecology Laboratory; 1315 Kinnear Road,*
*The Ohio State University, Columbus, OH 43212*

*ABSTRACT*: Hydraulic impacts represent a suite of habitat alterations that, although having different causes, often have similar methods of affecting the mussel fauna. For instance, logging and channelization are very different disturbances, but both generate sediments. These "hydraulic impacts" thus overlap each other to one degree or another. I have attempted to break them down into categories based on the type of disturbance, but what applies to 1 impact often may apply to others. By far, there is more published information on the effects of impoundments than on all other hydrologic impacts combined, and this review is dominated by that subject. Other subjects are not covered in any detail because they are too infrequent or ancillary to North American mussel conservation. For example, log runs in Finland are known to damage mussel populations (Valovirta 1990), but this is probably not a widespread problem.

**Keywords:** freshwater mussels, water quality, impoundments, hydrology, habitat

## Impoundments

Perhaps mankind's earliest attempt to manipulate free-flowing water was the dam. Dams could be used to divert water to mills and turbines, where its seemingly limitless power ground grain, cut lumber, and later generated electricity, generally freeing humanity to toil elsewhere. Dams could be used to divert water to irrigate ground that would not otherwise support crops. They could, in theory, alleviate flooding if the amount of water passing through the dam could be regulated. Dams could make a shallow river deep, allowing watercraft to operate. Impounded rivers could act as reservoirs for holding water to support the populace. Pristine natural areas could be turned into a recreational goldmine through impoundment. Real, perceived, or pork barrel, there were many reasons to dam rivers.

It must be stressed that an artificial impoundment is not analogous to a naturally occurring pool within a river. Impoundments typically become deeper toward their downstream end, until they abut the dam. In contrast, natural pools are deepest toward their middle, then becoming shallow, forming runs and riffles. This results in a very different water flow pattern through the pool/impoundment, and subsequently downstream. These hydrologic differences result in faunal differences. For example, van der Schalie (1938) found 15 mussel species in Lake Cooper, a man-made impoundment on the Mississippi River. In adjacent Lake Pepin, a naturally-formed pool, 30 species were encountered.

The general impact of impoundments on existing aquatic habitats was reviewed by many authors. Yeager's (1993, 1994) reviews are particularly thorough. Ellis (1942) gave an early review of the biotic and abiotic effects of impounding a river. He noted such deleterious consequences as silt accumulation, loss of shallow water habitat, stagnation, accumulation of pollutants, and nutrient-poor water. He concluded that "the initial period of high productivity may be very short in some reservoirs, and longer in others but the decline will inevitably come unless man makes some adjustments." Baxter (1977) gave an excellent review drawing from examples worldwide. The author characterized impoundments as a distinct type of ecosystem, characterized by complicated flow patterns that may involve hypolimnion discharge, long periods of flooding, and heavy sediment loads. Downstream areas may be affected as well, particularly by flow regime. Baxter sagely noted that "since not all the hydraulic head of the world's rivers has yet been utilized, it seems likely that more remain to be built." Neel (1963) gave a somewhat lopsided review of reservoirs, where they were largely viewed as desirable features. However, he "romantically" noted that fish migration was blocked, with "frustrated piscine migrants, monotonously working their way, time after time, toward the overpowering jets." Although the benthic fauna was "adversely affected," he speculated (in error) that "no certainty exists that missing species

---

[3] For correspondence contact G.T. Watters
(Email: watters.1@osu.edu)

have become extinct or cannot return." Despite Neel's (and others) claims, the evidence that impoundment is detrimental to aquatic life, and most mussels in particular, is overwhelming and indisputable.

Even below impoundments benthic diversity in general is reduced (Yeager 1993, 1994). We know that perhaps several dozen mussel species, and numerous more freshwater snails, were driven to extinction wholly or in large part by the construction of dams (Layzer *et al*. 1993, Lydeard and Mayden 1995, Stansbery 1973). Almost without exception, rivers that have been impounded, have lost or changed their mussel faunas.

**Examples**

**A. Tennessee River:** Isom (1969) reported that the Tennessee River's mussel diversity had decreased from 100 species to 44, largely because of changes associated with dams. Although caused in part by over-harvesting, the author attributed most of the decline to changes in habitat associated with the dam. Water flow in the impoundment had decreased to the point where silt could accumulate on the river bed, smothering mussels. Coincidentally, silt-tolerant species were expanding their ranges in the river.

In the Fort Loudoun Reservoir on the Tennessee River, Isom (1971) found a drastic decline in mussel diversity post-impoundment. A survey in 1970 of the reservoir found four mussel species. Prior to its impoundment, Ortmann (1918) reported 64 species from the same general area. In addition, the 1970 survey found mussels primarily on flooded pre-impoundment land (overbank), not in the original river channel habitat. This probably was due to critically depleted oxygen levels in the channel.

Elsewhere, during construction of the Nickajack Dam, the Tennessee River was dewatered at the construction site (Isom 1972). Seventeen species were found. Ortmann (1925) had found 25, for a cumulative total of 33 species reported for this reach. Missing in the latter survey were many endangered and rare species. Whether this was due to the presence of the Hales Bar Dam, 6.4 miles upstream, or other causes was not known.

It may be argued that mussel faunal composition changes over time whether dams are built or not. However, Parmalee *et al*. (1982) documented a fauna that remained essentially unchanged for several millennia until impounded by a dam. The Chickamauga Reservoir of the Tennessee River supported 46 species for perhaps 2,000 years prior to impoundment. After impoundment, 28 species were extirpated, and several are now extinct. Five species, mainly soft-substrate tolerant taxa, have invaded the reservoir. Four original species that survived the impoundment also have increased in abundance.

Mussel diversity has declined from 64 species to 30 in the upper Chickamauga Reservoir of the Tennessee River (Ahlstedt and McDonough 1994). Although relict populations of four federally endangered mussels still occurred there, based on pre-impoundment shell middens, two of these were once the most abundant species in the river reach.

In the Tennessee River portion of Wheeler Reservoir, 19 of the historical 38 species were either absent or present only as relicts (non-reproducing individuals) (Ahlstedt and McDonough, in press). Thick-shelled species may have been severely affected during a 6-y drought in the 1980's. Overall abundance had declined from an estimated 39 million mussels in 1960, to 14 million in 1991.

**B. Cumberland River:** At least 37 of the 60 pre-impoundment species of the Caney Fork River of the Cumberland River have been extirpated (Layzer *et al*. 1993). Two are extinct. The authors attributed this, in large part, to the presence of the Center Hill Dam. No living mussels were found for 12 km below the dam, which they attributed to the discharge of cold hypolimnetic water, periodic scouring, and dewatering. Near-anoxic conditions occasionally occurred in the metalimnion and hypolimnion of the impoundment. This acted as a barrier to fish movement across the impoundment, isolating mussel and fish populations in tributaries. Sedimentation of the impoundment also was taking place.

Schmidt (1986), in a separate survey, found 36 mussel species in the Caney Fork River prior to impoundment. By this estimate, the construction of the Center Hill hydroelectric dam resulted in the loss of 78% of those species. The author concluded that the extirpated species could not adapt to the widely fluctuating daily flows, cold water discharges, and loss of nutrients.

In "Lake" Barkley on the Cumberland River, 64% of the pre-impoundment mussel fauna was lost as a consequence of impoundment (Blalock and Sickel 1996). Prior to impoundment, 25 mussel species were reported from this reach. This study found only nine species 29 years after completion of the reservoir. However, 15 of the original species still occurred below the dam. Species had either invaded the impoundment, or once insignificant ones had became dominant, including anodontines and species of *Quadrula*. The authors attributed the overall decline, in part, to the accumulation of sediments, anoxic conditions in the impoundment, and loss of fish hosts.

In the lowest reach of the Cumberland River, only 25 of the 45 pre-impoundment mussel species remained (Sickel and Chandler 1996). Several new species had invaded, probably from the impounded Ohio River.

**C. Little Tennessee River:** Only 6 of the original 50 mussel species at Tellico Lake of the Little Tennessee River remained after impoundment (Parmalee and Hughes 1993). Although diversity had declined before completion of the dam, additional species were lost when they were impounded. By 1972, this diversity had dropped to 18 species. Twelve years after impoundment and the formation of Tellico Lake, only 6 of the original species still lived there. However, another 8 species were encountered for the first time. These species were apparently able to colonize the extensive sand/mud/silt substrate of the new embayments and overbanks.

**D. Kaskaskia River:** Forty mussel species were recorded from the Kaskaskia River prior to impoundment. Approximately 8 years after impoundment, only 24 species were found (Suloway *et al.* 1981). Some sites no longer supported any mussels, and overall density had declined. Once clean sand-gravel substrates were overlain with silt and debris caused by bank erosion, substrate instability, and runoff. Changes in host abundance also may have occurred.

**E. Tombigbee River:** The once highly diverse mussel fauna of the Tombigbee River was nearly obliterated by the construction of the Tenn-Tom Waterway and associated dams (Williams *et al.* 1992). Comparisons with unimpounded and pre-impounded areas revealed that perhaps two-thirds of the fauna were eliminated in impounded areas by loss of necessary habitat due to decreased water flow, increased depth, and sedimentation.

These and other case studies reveal clear-cut patterns and trends in the change associated with converting a free-flowing riverine habitat into an impoundment. Clearly, impoundments interfere with the basic ecological processes of free-flowing systems (Sparks 1995). Most indigenous mussel species are extirpated from the impounded region. These may be replaced by soft-substrate adapted species, such as anodontines and heelsplitters. The reason for this lies in the nature of the habitat modifications caused by impoundment.

### Mussel habitat in impoundments

A free-flowing river has great habitat heterogeneity: riffles, runs, pools, shoals, water-willow stands, and meanders, often with considerable tree canopy. After impoundment, 3 - 4 habitats remain, usually with no tree canopy. These are either new habitats or highly modified existing ones (Bates 1962, Blalock and Sickel 1996). These remaining habitats are discussed below.

### Original channel

The first is the original channel, which remains intact but under deeper water. Studies demonstrate that mussels, in general, are most abundant in shallow water, with relatively few species able to tolerate impoundment depths (Haukioja and Hakala 1974, Lewandowski and Stanczykowska 1975). Haag and Thorpe (1991) examined the relationship between depth and substrate type on benthic invertebrates at a site approximately 1.5 km downstream of Kentucky Lock and Dam on the Tennessee River. Although mussel abundance was not correlated with substrate type, abundance decreased with depth.

As water velocity decreases, water loses its ability to carry sediment. The old river channel effectively becomes a sediment “trap”, eventually smothering mussels that cannot adapt to soft substrates (Isom 1969). This is particularly true near the upstream side of the dam, where the substrate may be composed of mud mixed with debris and rubbish (Clark and Gillette 1911). Ellis (1936) summarized the effects of silt and sediment on the aquatic habitat in general, and on mussels in particular. Silt resulted in the loss of light penetration, causing diminished algal abundance, an important food of mussels. Thermal changes also occurred, specifically the creation of an annual lag in the cooling and warming of the hypolimnion. Silt caused organic material to be retained on the bottom, leading to oxygen depletion. And finally, silt smothered the benthic fauna. Ellis (1936) demonstrated this using over 2,000 mussels of 18 species in an artificial stream to which silt was added. A silt accumulation of 0.6–2.5 cm depth resulted in mortality approaching 90%.

Even before extirpation by smothering occurs, recruitment may be diminished or stopped, and growth rates reduced. Bates (1962), for example, found no evidence of mussel recruitment in the channel of Kentucky Lake, although adult mussels were present. Semenova *et al.* (1992) compared growth rates of *Margaritifera margaritifera* (Linnaeus, 1758) between rivers having different habitats, and found that rivers having high levels of suspended solids inhibited mussel growth. Bauer *et al*. (1980) determined that *M. margaritifera* juveniles required substrate with low organic content, conditions not met in submerged channels. Buddensiek *et al*. (1993) showed that juvenile mussels, which live completely buried for several years, required a substrate where water could be freely exchanged between the overlying water column and the interstitial water. These interstices are clogged by silt in impoundment conditions.

The hypolimnion of the channel also may become excessively cold, near-anoxic, and nutrient-poor. Cold water (<11 °C) has been shown to stunt the growth of mussels (Ghent *et al*. 1978, Harman 1974, Semenova *et al*. 1992). Hanson *et al*. (1988) showed that individuals of *Pyganodon grandis* (Say, 1829) grew slower in deeper water in a natural lake than in shallows, due to differences in temperature. The same would be true for mussels living in cold water discharges. Because mussel reproduction is temperature dependent, it is likely that individuals living in the constantly cold hypolimnion in these channels may never reproduce, or reproduce less frequently. Hruska (1992) showed that mussels require a minimum number of degree-days and sustained warm water temperatures for gametogenesis to take place. Undoubtedly some mussel populations living in the hypolimnion of impoundments are not reproducing simply because the thermal cues needed to start gametogenesis no longer occur. In addition, some channels are subjected to depleted oxygen levels (Blalock and Sickel 1996, Isom 1971, Layzer *et al*. 1993) and may become nutrient-poor (Ellis 1942, Harman 1974).

Over time, the original mussel species composition of the channel may be eliminated (Holland-Bartels 1990) or changed in favor of silt-tolerant species, such as anodontines and species of *Leptodea* and *Potamilus* (Bates 1962, Blalock and Sickel 1996, Clark and Gillette 1911, Ellis 1931, Isom 1969, Klippel and Parmalee 1979, Parmalee and Hughes 1993). Most of these silt-tolerant species are of no commercial value nor protected taxa. Not surprisingly, dams were implicated in the loss of commercial mussel beds by Ellis (1931). Klippel and Parmalee (1979) reported that the diversity of species in "Lake" Springfield (Illinois River) was the same before and after impoundment. However, the relative abundance of the species changed. Soft-sediment adapted species were more common than before impoundment. An additional 3 sediment-tolerant mussel species were found after impoundment as well. Thus, the new composition may include species that did not occur there prior to impoundment, and are of no commercial or conservation importance. Although there is conflicting evidence as to what degree mussels are habitat specific, the change from a sand/gravel/cobble bottom to one overlain with silt entails at least a change in relative abundance from the original fauna, if not the loss of original species (Burkhead *et al*. 1992, Layzer *et al*. 1993, Williams *et al*. 1992). Harman (1972) believed that freshwater mollusks had substrate preferences. He showed that species occurring in clean grave-cobble did not occur in silt, and vice versa. In another study, Ghent *et al*. (1978) examined the distributions of *Elliptio*, a silt-intolerant species, and *Anodonta*, a silt-tolerant one, in natural a lake. *Elliptio* was most common in shallow water in sand, and *Anodonta* was most common in deeper water in silt. Holland-Bartels (1990) also examined substrate preference by mussels in an impounded portion of the Mississippi River. Mussels showed a wide tolerance for substrate type but many species were less abundant in finer sediments. She believed that as the impoundment continues to fill with silt, some species may be lost. Watters and Dunn (1995) demonstrated that mussel distributions in the Muskingum River had changed due to construction of dams. Pre-impoundment mussel distributions were fairly uniform in the river. Mussels were now limited to within a few miles downstream of each dam. This region represented the only portion of the river that was still highly oxygenated and swept clean of silt. Further downstream of dams, water velocity decreased and a mud/silt substrate prevailed devoid of most mussels. Obviously, changing a habitat through artificial modifications changes a molluscan fauna.

### Floodplains

A second, new habitat formed by impoundment is the overbank, composed of the inundated pre-impoundment floodplains and other adjacent dry lands. Typically this habitat is dominated by mud or sand-mud substrates in shallow water (Bates 1962). Although this habitat may support dense mussel populations, they tend to be composed of soft-substrate species and some species of *Quadrula* (Isom 1971, Parmalee and Hughes 1993).

### Embayments

Embayments and coves represent a third impoundment habitat. These areas are inundated and usually experience the same siltation problems as the floodplains (Blalock and Sickel 1996). Embayments may encroach upon and adversely affect otherwise high diversity tributaries (Harman 1974). Schuster *et al*. (1989) found that Buck Creek was an important refugium for mussels extirpated from the Cumberland River. But downstream, the impounded "Lake"

Cumberland River periodically backed up into Buck Creek. The substrate there was soft mud, and was nearly devoid of mussels.

### Beachs

Finally, a narrow sandy beach often is formed by impoundments. However, fluctuating water levels and unstable substrates usually render this habitat unsuitable for mussels. For example, in the upper Tennessee River valley, impoundment levels are often dropped drastically during winter months to develop a "buffer" for possible flood control with the spring rains. This "dewatering" usually leaves much of the previously inundated shoreline exposed (> 25 m), and any new juvenile mussels that may been deposited there earlier in the year, now exposed.

### Dams and impoundments as barriers to mussels and hosts

It was recognized early that dams acted as barriers to fish movement (Coker 1914). Coker (1914) believed impoundments had both good and bad qualities for mussels, and envisioned the tremendously increased surface area of flooded dry land as potential mussel and fish habitat. But he realized that dams would form effective barriers to fish host dispersal. Hubbs and Pigg (1976) showed that the decline in fish diversity in Oklahoma was due, at least in part, to these barriers. Migrating fishes, in particular, would be affected (Coker 1914, Branson 1974, Unkenholz 1986, Alexander 1987). Some fishes are now rare, due in large part to these migration obstacles (Stuebner 1993). In some cases, such as the Hells Canyon Complex in Idaho, migration has become impossible for some species of fishes (Collier *et al*. 1996). For freshwater mussels, this meant that hosts may not be accessible to their glochidial parasites. Otherwise healthy mussel populations would simply grow old and die without recruiting. Such a loss of hosts has been implicated in the decline of mussels in several areas (Burkhead *et al*. 1992, Jones 1991, Suloway *et al*. 1981). Watters (1996) showed that dams as low as 1 m in height restricted the distribution of some mussel species. Because the dams caused minimal habitat disturbance, this effect was probably due to interference with host movements and migrations. Even if not absolutely trapped by dams, the route a fish must take to surmount a dam are often circuitous and, at best, unlikely. Clark and Gillete (1911) noted that as the result of Sullivan's Dam on the Little River, a fish trying to move upstream would have to backtrack downstream to the Big Arkansas River, enter Chisholm Creek and move upstream until it encountered a cut-off ditch that communicated back to the Little River above the dam. Even then, this ditch ended in a floodgate that was only open during normal flow. Impoundments themselves, beyond the physical presence of the dam, may act as barriers to hosts as well. Turbid, anoxic water in the main impoundment may isolate mussels and fishes in tributaries (Layzer *et al*. 1993).

### Mussel habitat in tailwaters

The habitat in the tailwaters is influenced by the dam (Ligon *et al*. 1995). Depending on the use of the dam, water levels may fluctuate on a regular interval (for hydroelectric purposes) or at random (for flood control). In some areas, water levels may be become shallow enough that thermal buffering is lost, allowing extreme temperatures to occur. Blinn *et al*. (1995) reported that substrate subjected to 2-12 h exposures to air required more than 4 mo. to regain a biomass similar to unexposed habitat. Federally endangered mussel species were reported by Neck and Howells (1994) as casualties of scheduled dewatering processes. Riggs and Webb (1956) reported that several thousand mussels died in the tailwaters of Lake Texoma, an impoundment of the Red River formed by Denison Dam, when water levels dropped, allowing the water to become excessively warm (>26 °C). This area was exposed for at least 20 days before being again inundated. Exposure to cold air may be equally lethal. Nagel (1987) believed mussels were more sensitive to cold water during frosts than warm water during temporary droughts, and Blinn *et al*. (1995) showed that a single overnight exposure to subzero temperatures resulted in at least a 90% loss of invertebrate mass. Valovirta (1990) reported that mussels were killed when water froze to the river bottom.

Harman (1974) found few mussels within the first 17-34 km below impoundments in the Delaware River system due to cold water discharges. Low temperatures associated with an impoundment hypolimnion were thought to result in slow growth and inhibited reproduction. This was dramatically shown by Heinricher and Layzer (1999), who transplanted non-reproducing mussels out of a cold water discharge to warmer water where the mussels began to reproduce.

Associated with fluctuating water levels are dramatic changes in water velocity. Neck and Howells (1994) noted that high-volume water discharges and abrupt stoppages resulted in a river bed composed of large rocks and shifting sand, habitat inhospitable to most mussels. In the River Schwalm in Germany, Nagel (1992) compared growth rates of three mussel species (*Unio pictorum*, *Pseudanodonta complanata*, *Anodonta* *piscinalis*) along the length of the river. Little change in growth rate was associated with either cool- or warm-water discharges. More important were differences in water flow velocity. A similar result was found for the declining mussel population in the Licking River of Kentucky (McMurray *et al*., 1999). The authors believed that spikes of cold hypolimnionic discharge from the Cave Run Lake dam was more important to the mussel fauna than were changes in long-term discharges. Scour immediately below dams also may preclude colonization by mussels (Miller and Payne 1992). These authors characterized a large mussel bed below a dam by density, recruitment rates, and demography. Compared with earlier surveys, there was little indication that this bed had changed as the result of the presence of the dam, except the area closest to the dam. That area experienced greater scour and erosion than downstream and had less mussel diversity. However, in other rivers this unstable zone may be extensive. In Texas, the Possum Kingdom Reservoir on the Brazos River exhibited unstable substrate for 150 km below the dam (Yeager 1993). These areas of erosion may move downstream at a rate of up to tens of km $yr^{-1}$ (Fedorov 1969) until water velocity falls below the threshold necessary to transport sediments (Yeager 1993).

Beyond the area of scour sedimentation below dams may be extreme. The Rio Grande at El Paso, below the Elephant Butte Dam, accumulated nearly 4 m of sediment in 26 y (Reinhardt 1937). This sedimentation reduced fish diversity and abundance by altering habitat necessary for spawning and overwintering (Petts 1984, Holland and Huston 1985, Nelson *et al*. 1987). Changes in fish faunal composition as the result of impoundments have been demonstrated for the Clinch River in Tennessee (Fitz 1968), the Barren River in Kentucky (Swink and Jacobs 1983), and the Guadeloupe River in Texas (Edwards 1978).

Clearly, silt deposited in the tailwaters may smother mussels. But Chutter (1969) showed that even sublethal amounts of silt and sand rendered the tailwaters inhospitable. In case studies on aquatic invertebrates in South Africa, he found that increases in the amount of sand and silt below dams caused instability of the river substrate. Therefore, it was not necessary to smother the substrate before deleterious changes in habitat occurred. Neck and Howells (1994) proposed this as one cause (of several) for the decline of the imperiled *Potamilus amphichaenus* (Frierson, 1898).

### Dikes and levees

The overall biotic and abiotic impacts of dikes and levees were summarized by Pennington and Shields (1993). In otherwise habitat-homogeneous impounded rivers, these structures may offer a small measure of habitat diversity for some macroinvertebrates (Beckett *et al*. 1983, Burress *et al.* 1982). However, dikes and levees often trap fine-grained sediments. These areas would be colonized by soft-substrate adapted mussels. The rip-rap often used with these structures would not be suitable for colonization by mussels (Libois and Hallet-Libois 1987).

### Upland reservoirs and changes in the water table

There is little information on the effects of upland reservoirs on mussel communities. Hauck and Edson (1976) discussed some consequences on fishes of upland storage ponds used for hydroelectric generation. Some of these effects influence mussels, directly or indirectly. Pumping cycles produce fluctuating water levels that adversely affect mussels. Hosts also may be entrained incidentally by water intakes.

### Land use practices

Logging, mining, construction, farming, livestock, and a host of other land uses often adversely affect mussel populations, generally by releasing runoff of sediments, salt, and other pollutants into the stream, as well as an increased volume of water (Allan and Flecker 1993, Osborne and Kovacic 1993, Patric and Aubertin 1977). Houp (1993) documented that an otherwise pristine Wild River segment of the Red River in eastern Kentucky, was experiencing a decline in mussels due to sedimentation from mining, stream-relocation, logging, and farming, although these occurred miles upstream of the effected area. The result was a changing mussel community composition favoring more tolerant and less habitat-specific species. A similar condition was reported for the Buttahatchee River, Mississippi (Jones 1991), where mussel surveys in 1990 demonstrated pronounced declines in several areas since 1977. These declines were attributed to impoundment associated with the Tenn-Tom Waterway, increased turbidity from an abandoned kaolin strip mine, runoff from logging areas, and sand and gravel mines. The substrate was unstable at several sites, perhaps due to gravel mining. Bank erosion had resulted from the removal of the riparian corridor through logging or agriculture. Mussel populations in the Powell River, Virginia based on early surveys of the 1900's, were degraded by land mismanagement (Wolcott and Neves 1994). Runoff from coal mines, abandoned mine lands, and wastewater treatment plant effluents all had contributed to the decline. Although mussels still lived at most sites, virtually no recruitment was found. Woodward (1990) noted several changes in land use in Scotland that harmed existing mussel populations: strip mines and peat extraction contributed to sediment and acid water runoff; fish farms discharged waste; and improvements in the road system allowing easier access to streams not only to pearl fishers, but to tourists, skiers, divers, and hikers, which were "counter-productive due to their increasing presence through ready access resulting in the destruction of the natural environment which drew them to the area in the first place." Proximity of streams to roads may be detrimental by increasing the amount of salt, heavy metals, petroleum products, and other pollutants washed into the system (Van Hassel *et al*. 1980, Winger *et al*. 1985). With runoff, changes in host composition may occur as well (Boschung and O'Neil 1981, Berkman and Rabeni 1987, Houp 1993, Rutherford *et al*. 1992). Finally, sediments from channelization and other sources of runoff erode mussel shells rendering them susceptible to shell-dissolving acids (Harmon 1974).

Where recognized, erosional problems often require bank stabilization practices. Libois and Hallet-Libois (1987) examined four mussel species in the River Meuse in Belgium during a maintenance dewatering. The banks of the river varied from several types of natural substrate to man-made reinforcements: riprap, gabions, concrete, and open stone pitching. Mussel density was highest in the natural habitats of mud, sand, and fine gravel, and lowest by several orders of magnitude on man-made reinforcements. They concluded that mussel density was significantly lower in the "stabilized" areas than in unaltered habitat.

Land mismanagement need not be confined to physical destruction of the riparian corridor. In an age when everyone wants stream-front property with a green lawn to the water's edge, obvious habitat alterations become apparent. Morris and Corkum (1996) studied differences in mussel community composition between a forested riparian corridor and one composed of grass. They found greater temperature fluctuations and higher ammonia and nitrogen concentrations at the grassy site. Although the two types of sites had the same mussel diversity, the grassy site was dominated by an anodontine species. The authors suggested that species had a higher tolerance to the fluctuating temperature and different chemical composition found there.

### Watercraft

Watercraft, particularly large vessels such as tugs pushing barges, cause changes in habitat, and may affect mussels in and adjacent to navigation channels. Water turbulence increases as vessels pass by, creating short-lived surges. These surges stir-up bottom sediments, and increase the amount of suspended solids for undetermined amounts of time. Muddy plumes behind tugs are not uncommon, indicating that bottom sediments have been forcibly removed from the channel and suspended. (Apocryphal reports exist of mussels being lifted from the bottom into tug propellers.) Wake impinging on the shoreline may escalate erosion and introduce additional suspended solids into the water. It is believed that these factors interfere with mussel respiration and/or feeding, and may result in diminished health in mussels in these areas.

Aldridge *et al*. (1987) studied the effect of propeller-induced turbulence in controlled laboratory conditions by exposing mussels to varying levels of suspended solids and periods of turbulence and measuring physiological rates. They concluded that frequent turbulence (once every 0.5 h) and high concentrations of suspended solids (600-750 mg $L^{-1}$) changed the physiological energetics of the mussels by significantly decreasing food clearance rates and oxygen uptake, and nitrogen elimination. However, Miller and Payne (1995), in an *in situ* study, investigated the possible effects of navigation traffic on mussel beds in the Ohio River. They concluded that although there were changes in water velocity associated with passage, the duration was too short and the velocity change too small to affect mussels. Clearly, more work needs to be done on this important aspect of mussel conservation and management.

### Trampling

There is very little literature addressing the issue of trampling on mussels. By this I mean the physical destruction to individual mussels caused by being crushed by people, animals, and machinery. As early as the 1700's, Scottish and German pearl fishers realized that mussels downstream of fords often had more pearls than in other places (Kunz and Stevenson 1908). This was due, no doubt, to the increased sediments (that became the pearl nuclei) generated by horses and wagons crossing the fords. In areas where livestock have access to a waterway, crushed mussels, broken shells, and deformed living individuals are not uncommon. Similarly, fords across streams are often rendered devoid of mussels. In areas where waterways have a firm substrate, the practice of driving offroad vehicles in the river may be a chronic problem. However these usually represent fairly insignificant nuisances that act on small areas.

More serious is the problem posed by canoeists and naturalists, who pose a peculiar paradox. Although these people are often supportive and appreciative of natural areas, the portage of canoes and people across riffles and runs must have a deleterious impact on mussels, particularly juveniles. Juveniles and adult mussels live buried in these riffles. Hosts (*e.g.*, darters, sculpins) must frequent these riffles to be parasitized. I have witnessed up to 40 canoes an hour being dragged across riffles supporting federally endangered species in Big Darby Creek, Ohio. This scenario, played repeatedly at every riffle, may have a substantial effect on mussel populations. There is no doubt that the presence of hikers, divers, skiers, and tourists may be detrimental to a natural area (Woodward 1990). Denying use of this recreation, however, could have negative political and social repercussions.

### Channelization, dredging and snagging

Channelization, dredging, and snagging, like impoundment, reduce habitat heterogeneity and aquatic diversity (Nelson 1993). Meanders are removed (Simpson *et al*. 1982) and the riffle-run-pool sequence is disrupted (Keller 1978, Wesche 1985) reducing available fish and mussel habitat. Circulation patterns and substrate composition are altered (Loar *et al*. 1980). Macroinvertebrate assemblages and trapped organic matter that form integral parts of the trophic web are eliminated (Cummins *et al*. 1973, Ebert 1993). Potential mussel hosts may be lost as fish faunal composition changes. Examples of fish faunal changes associated with channelization and dredging were documented in Mississippi (Arner *et al*. 1976), Ohio (Trautman and Gartman 1974), Illinois (Smith 1968, 1971), and Pennsylvania (Lee 1973).

The process of dredging and channelization may be catastrophic. Most obviously, mussels caught in the dredge path are destroyed. But the effects of channelization are more far-ranging than just the immediate dredge area. Silt and other suspended solids generated by channelization may travel downstream and smother, or otherwise adversely affect mussels. Instream dredging for minerals has similar effects. Marking (1979) buried 3 mussel species to depths of 25 cm to determine how much smothering they could survive. Fifty percent of *Lampsilis cardium* (Rafinesque, 1820) and *Lampsilis radiata* (Gmelin, 1791) individuals were able to extricate themselves from up to 17.5 cm in depth. Fifty percent of *Fusconaia flava* (Rafinesque, 1820) individuals were able to extricate themselves from up to 10 cm in depth. But Ellis (1942), working with over 2,000 mussels of 18 species, reported that 90% mortality occurred with 25 mm of siltation. Granted that dredge spoil and silt may be two different things, but the disparity of these results beg for additional tests. Besides smothering, sediments resulting from channelization may resuspend contaminants (Engler 1979), increase concentrations of inorganic plant nutrients, lower photosynthesis (Loar *et al*. 1980), and increase BOD (Ebert 1993). Sediments generated by channelization may eventually erode shells, rendering them more susceptible to shell-dissolving acids (Harman 1974).

Full-scale dredging is not necessary to disrupt mussel populations. Valovirta (1990) noted that simply removing large rocks from the channels to facilitate water flow caused the substrate to become unstable, resulting in mussel mortality. In southern Europe, *M. margaritifera* was found in only 25% of its original range, and many populations were not reproducing (Bauer 1986). Bauer attributed this decline largely to eutrophication through pollution, but several cases were given of channelization adversely affecting mussel populations. Although there is not a large body of literature on the impact of channelization to mussels, channelization has been implicated in mussel declines (Grace and Buchanan 1981, Hartfield 1993, Schuster *et al*. 1989, Valovirta 1990, Yokley and Gooch 1976).

As the forces of nature attempt to reclaim these altered habitats, it becomes necessary to perform maintenance to preserve the existing modifications. Channels dredged for navigation or flood control quickly begin to refill, requiring a periodic re-dredging to ensure a minimum depth. Impoundments are dredged to maintain storage capacity. Dredge spoil and associated contaminants disposed of in upland areas may inevitably re-enter the river through surface runoff, biological uptake and cycling, and leaching into groundwater (Gambrell *et al*. 1978). The problems associated with channelization thus become chronic, resulting in long-term ecological changes.

Channelization may result in an increase in soft-substrate adapted mussels. Increasing the depth of channels may lower water velocity, causing sedimentation to take place (Hubbard *et al*. 1993), allowing these mussels to colonize the new habitat. On one occasion this increased the population of an endangered mussel species. The federally endangered *Potamilus capax* (Green, 1832) had colonized portions of the severely channelized St. Francis River flood-control channels in Arkansas (Ahlstedt and Jenkinson 1987). The modification had resulted in an apparently optimum habitat for that soft-substrate tolerant species. Many of these mussels were relocated when re-channelization became necessary. The Hocking River in Ohio, channelized for flood control, was colonized by several otherwise uncommon species, including a then state endangered species (Watters 1988). These were all soft-substrate adapted species. It must be emphasized that these are unusual cases and that despite their rarity, these new mussel faunas flourished at the expense of the original faunas. Furthermore, most dredged areas are not quickly colonized by mussels of any kind. For example, Grace and Buchanan (1981) found no mussels in an area dredged 15 y earlier.

Snagging is a common practice to alleviate perceived "flooding" (*i.e.*, preventing a river from inundating its natural floodplain). Fallen trees and debris are removed by dragging them from the stream bed. This action inevitably reduces the available habitat by creating a more homogeneous environment (Marzolf 1978). Habitat heterogeneity is important to fish diversity, and therefore mussel diversity. Snagging increases bank erosion (Hubbard *et al*. 1993) and creates unstable substrates as the stream recovers (Cobb and Kaufman 1993).

Channelization and snagging may actually increase flood heights (Belt 1975). This is due, in part, to a reduction of stream length and increased gradient (Hubbard *et al*. 1993). (One stretch of the Rio Grande, for instance, was shortened from 155 miles to 88 miles (Mueller 1975)). These amplified flood events create additional runoff, and additional remediation.

### Headcutting

Headcuts are regions of disturbance moving upstream, in a zipper-like fashion, as the result of the upper boundary of the modification collapsing. Headcuts may move miles upstream, destroying habitat and mussels as they pass. Headcutting is a form of channel modification that has operated undetected on many rivers and streams (Hartfield 1993). Instream modifications such as dredging obviously affect the mussels in the immediate area, as well as those downstream. But sometimes, mussels above the modification become extirpated as well.

### Canals

To our ancestors, traveling on rivers was much easier than traveling by land, as long as the river went where you wanted it to go. It quickly became apparent that divine provenance had not placed rivers where they should be, an oversight humanity attempted to rectify. By digging canals between rivers and lakes, watercraft could move great distances without laborious portage. No thought was given to the possibility that connecting two different river systems possessing different faunas might not be a desirable goal. Nevertheless, once connected, we know that fishes and mussels populated these canals and certainly must have moved between systems. What effect this had on mussel and host distributions cannot be ascertained; the event is too distant in time with sketchy baseline data for comparison. While it might be assumed that these canals were sediment laden, supporting only anodontines and other soft-substrate tolerant species, this was not always the case. Higgins (1858) described the Columbus [Ohio] feeder canal of the Ohio Canal: "Many species have traversed the whole length of the canal, and many species there thrive and become abundant which are quite rare in the adjacent rivers." Records at the Carnegie Museum of Natural History, Pittsburgh, also document now endangered species living in these canals.

Most of these canals are now abandoned and no longer maintain connections between rivers. However, in Texas, connections recently have been made between the Red and Trinity Rivers. Plans also are being considered to move water from the Neches or Sabine River, across the Trinity, Brazos, and Colorado River systems, to the Lavaca-Navidad, to be removed downstream for transfer to Corpus Christi (Howells *in lit.* 1997).

## Summary

Hydraulic impacts on freshwater mussel habitats are often catastrophic, both immediately and over time. Most such impacts involve complicated interrelated actions; rarely is there a single causative agent for mussel declines. For example, although impoundments may lead to the immediate smothering of some mussels, many effects may take years to become apparent: changes in seasonal temperatures within the impoundment, isolation from necessary hosts, changes in component fauna, etc.

The data clearly support the fact that impoundments, dredging, snagging, channelization, and other improvements once taken for granted may have long-term detrimental effects on freshwater mussels. In many cases these changes appear to be irreversible. Dozens of freshwater mussels and snails have become extinct within the past 200 years as the result of these practices. Although our knowledge of these animals has dramatically increased in the past decades, it is now apparent that their basic biology is much more complex than ever imagined. Our future use and alteration of their habitat must be carefully planned with this knowledge in mind to prevent any further irrevocable loss of biodiversity.

## Literature Cited

**Ahlstedt, S.A. and J.J. Jenkinson. 1987.** Distribution and abundance of *Potamilus capax* and other freshwater mussels in the St. Francis River system, Arkansas and Missouri. U.S. Army Corps of Engineers, Memphis District, Tennessee. Contract No. PD-86-C052. 164 pp.

**Ahlstedt, S.A. and T. McDonough. 1994.** Summary of preoperational monitoring of the mussel fauna in upper Chickamauga Reservoir in the vicinity of the Watts Bar Nuclear Plant 1983-1993. Tennessee valley Authority, Water Management Environmental Compliance, Norris, TN. 29 pp.

**Ahlstedt, S.A. and T. McDonough. 1993.** Quantitative evaluation of commercial mussel populations in the Tennessee River portion of Wheeler Reservoir, Alabama. Pages 38-49. *In* K. S. Cummings, A. C. Buchanan, and L. M. Koch (editors) Conservation and Management of Freshwater Mussels. Proceedings of a UMRCC Symposium, October 1992, St. Louis, Missouri. Upper Mississippi River Conservation Committee, Rock Island, Illinois.

**Aldridge, D.W., B.S. Payne, and A.C. Miller. 1987.** The effects of intermittent exposure to suspended solids and turbulence on three species of freshwater mussels. Environmental Pollution 45: 17-28.

**Alexander, C.M. 1987.** Fishery status assessment of Watts Bar Reservoir with management recommendations. Unpublished report, Tennessee Valley Authority TVA/ONR/WRF-83/4(a), Knoxville.

**Allan, J.D. and A.S. Flecker. 1993.** Biodiversity conservation in running waters. BioScience 43: 32-43.

**Arner, D.H., Robinette, H.R., Frasier, J.E. and M.H. Gray. 1976.** Effects of channelization of the Luxipalila River on fish, aquatic invertebrates, water quality, and furbearers. Unpublished report, US Fish and Wildlife Service FWS/OBS-76-08, Fort Collins, Colorado.

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

**Bauer, G. 1986.** The status of the freshwater pearl mussel *Margaritifera margaritifera* L. in the south of its European range. Biological Conservation 38: 1-9.

**Bauer, G., Schrimpff, E., Thomas, W., and R. Herrmann. 1980.** Zusammenhänge zwischen dem Bestandsrückgang der Flußperlmuschel (*Margaritifera margaritifera*) im Fichtelgebirge und der Gewässerbelastung. Archiv für Hydrobiologie 88: 505-513.

**Baxter, R.M. 1977.** Environmental effects of dams and impoundments. Annual Review of Ecology and Systematics 8: 255-283.

**Beckett, D.C., Bingham, C.R., Sanders, L.G., Mathais, D.B., and E.M. McLemore. 1983.** Benthic macroinvertebrates of selected aquatic habitats on the lower Mississippi River. Unpublished Report E-83-10, US Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi.

**Belt, C.B. 1975.** The 1973 flood and man's constriction of the Mississippi River. Science 189: 681-684.

**Berkman, H.E. and C.F. Rabeni.** 1987. Effect of siltation on stream fish communities. Environmental Biology of Fishes 18: 285-294.

**Blalock, H.N. and J.B. Sickel. 1996.** Changes in mussel (Bivalvia:Unionidae) fauna within the Kentucky portion of Lake Barkley since impoundment of the lower Cumberland River. American Malacological Bulletin 13: 111-116.

**Blinn, D.W., Shannon, J.P., Stevens, L.E., and J.P. Carder. 1995.** Consequences of fluctuating discharge for lotic communities. Journal of the North American Benthological Society 14: 233-248.

**Boschung, H.T. and P. O'Neil. 1981.** The effects of forest clear-cutting on fishes and macroinvertebrates in an Alabama stream. Pp. 200-217 *In* L.A. Krumholz, C.F. Bryan, G.D. Pardue, and G.A. Hall (editors), Proceedings of the Warmwater Stream Symposium, Southern Division of the American Fisheries Society, Bethesda, MD.

**Branson, B.A. 1974.** American paddlefish: signs of distress. National Parks and Conservation Magazine 48(1): 21-23.

**Buddensiek, V., Engel, H., Fleischauer-Rössing, S., and K. Wächtler. 1993.** Studies on the chemistry of interstitial water taken from defined horizons in the fine sediments of bivalve habitats in several northern German lowland waters. II: Microhabitats of *Margaritifera margaritifera* L., *Unio crassus* (Philipsson) and *Unio tumidus* Philipsson. Archiv für Hydrobiologie 127: 151-166.

**Burkhead, N., Williams, J., and B.J. Freeman. 1992.** A river under siege. Georgia Wildlife 2(2): 10-17.

**Burress, R.M., Krieger, D.A., and C.H. Pennington. 1982.** Aquatic biota of bank stabilization structures on the Missouri River, North Dakota. Unpublished Report E-82-6, U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi.

**Chutter, F.M. 1969.** The effects of silt and sand on the invertebrate fauna of streams and rivers. Hydrobiologia 34: 57-76.

**Clark, H.W. and G.H. Gillette. 1911.** Some observations made on Little River, near Wichita, Kansas, with reference to the Unionidae. Proceedings of the Biological Society of Washington 24: 63-68.

**Cobb, S.P. and J. Kaufman. 1993.** Clearing and snagging. Pp. 169-180, *In* Bryan, C.F. & D.A. Rutherford (editors), Impacts on warmwater streams: guidelines for evaluation. Southern Division, American Fisheries Society, Little Rock, Arkansas.

**Coker, R.E. 1914.** Water-power development in relation to fishes and mussels of the Mississippi. Report of the U.S. Commissioner of Fisheries for 1913, Appendix 8: 1-28.

**Collier, M., Webb, R.H., and J.C. Schmidt. 1996.** Dams and rivers. U.S. Geological Survey, Circular 1126. 94 pp.

**Cummins, K.W., Peterson, R.C., Howard, F.O., Wycheck, J.C., and V.I. Holt. 1973.** The utilization of leaf litter by stream detritivores. Ecology 54: 336-345.

**Ebert, D.J. 1993.** Dredging. Pp. 157-167, *In* Bryan, C.F. & D.A. Rutherford (editors), Impacts on Warmwater Streams: Guidelines for Evaluation. Southern Division, American Fisheries Society, Little Rock, Arkansas.

**Edwards, R.J. 1978.** The effect of hypolimnion reservoir releases on fish distribution and species diversity. Transactions of the American Fisheries Society 107: 71-77.

**Ellis, M.M. 1931.** A survey of conditions affecting fisheries in the upper Mississippi River. Bureau of Fisheries, Fishery Circular 5: 1-18.

**Ellis, M.M. 1936.** Erosion silt as a factor in aquatic environments. Ecology 17: 29-42.

**Ellis, M.M. 1942.** Fresh-water impoundments. Transactions of the American Fisheries Society, 71st Annual Meeting, 80-93.

**Engler, R.M. 1979.** Bioaccumulation of toxic substances from contaminated sediments by fish and benthic organisms. Pages 325-354 *In* S.A. Peterson, and K.K. Randolph (editors), Management of Bottom Sediments Containing Toxic Substances. Proceedings of the 4th United States-Japan Experts Meeting, Tokyo. U.S. Environmental Protection Agency EPA 600-3-79-102. Corvallis, OR.

**Fedorev, B.G. 1969.** Erosion below hydro-electric dams. Trudy Tsnievt 58: 1.

**Fitz, R.B. 1968.** Fish habitat and population changes resulting from impoundment of Clinch River by Melton Hill Dam. Journal of the Tennessee Academy of Science 43: 7-15.

**Gambrell, R.P., Khalid, R.A., and W.H. Patrick. 1978.** Disposal alternatives for contaminated dredged material as a management tool to minimize adverse environmental effects. Unpublished report DS-78-8, US Army Engineer Waterways Experiment Station. 148 pp.

**Ghent, A.W., Singer, R. and L. Johnson-Singer. 1978.** Depth distributions determined with SCUBA, and associated studies of the freshwater unionid clams *Elliptio complanata* and *Anodonta grandis* in Lake Bernard, Ontario. Canadian Journal of Zoology 56: 1654-1663.

**Grace, T.B. and A.C. Buchanan. 1981.** Naiades (mussels) of the lower Osage River, Tavern Creek, and Maries River, Missouri. Unpublished report, Missouri Department of Conservation, Jefferson City. 147 pp.

**Haag, K.H. and J.H. Thorp. 1991.** Cross-channel distribution patterns of zoobenthos in a regulated reach of the Tennessee River. Regulated Rivers: Research & Management 6: 225-233.

**Hanson, J.M., Mackay, W.C., and E.E. Prepas. 1988.** The effects of water depth and density on the growth of a unionid clam. Freshwater Biology 19: 345-355.

**Harman, W.N. 1972.** Benthic substrates: their effect on fresh-water Mollusca. Ecology 53:271-277.

**Harman, W.N. 1974.** The effects of reservoir construction and channelization on the mollusks of the upper Delaware watershed. Bulletin of the American Malacological Union for May 1974: 12-14.

**Hartfield, P. 1993.** Headcuts and their effect on freshwater mussels. Pp. 131-141. *In* K.S. Cummings, A.C. Buchanan, and L.M. Koch (editors). Conservation and Management of Freshwater Mussels. Proceedings of a UMRCC Symposium, October 1992, St. Louis, Missouri. Upper Mississippi River Conservation Committee, Rock Island, Illinois.

**Hauck, F.R. and Q.A. Edson. 1976.** Pumped storage: its significance as an energy source and some biological ramifications. Transactions of the American Fisheries Society 105: 158-164.

**Haukioja, E. and T. Hakala. 1974.** Vertical distribution of freshwater mussels (Pelecypoda, Unionidae) in southwestern Finland. Annales Zoologici Fennici 11: 127-130.

**Heinricher, J.R. and J.B. Layzer. 1999.** Reproduction by individuals of a nonreproducing population of *Megalonaias nervosa* (Mollusca: Unionidae) following translocation. American Midland Naturalist 141: 140-148.

**Higgins, F. 1858.** A catalogue of the shell-bearing species of Mollusca, inhabiting the vicinity of Columbus, Ohio, with some remarks thereon. Ohio State Board of Agriculture with an Abstract of the Proceedings of the County Agricultural Society's 12th Annual Report, for 1857: 548-555.

**Holland, H.E. and M.L. Huston. 1985.** Distribution and food habits of young-of-year fishes in a backwater lake of the upper Mississippi River, USA. Journal of Freshwater Ecology 3: 81-92.

**Holland-Bartels, L.E. 1990.** Physical factors and their influence on the mussel fauna of a main channel border habitat of the upper Mississippi River. Journal of the North American Benthological Society 9: 327-335.

**Houp, R.E. 1993.** Observations on long-term effects of sedimentation on freshwater mussels (Mollusca: Unionidae) in the North Fork of Red River, Kentucky. Transactions of the Kentucky Academy of Science 54: 93-97.

**Hruska, J. 1992.** The freshwater pearl mussel in South Bohemia: evaluation of the effect of temperature on reproduction, growth and age structure of the population. Archiv für Hydrobiologie 126: 181-191.

**Hubbard, W.D., Jackson, D.C., and D.J. Ebert. 1993.** Channelization. Pages 135-155. *In* Bryan, C.F. & D.A. Rutherford (editors). Impacts on warmwater streams: guidelines for evaluation. Southern Division, American Fisheries Society, Little Rock, Arkansas.

**Hubbs, C. and J. Pigg. 1976.** The effects of impoundments on threatened fishes of Oklahoma. Annals of the Oklahoma Academy of Science 5: 133-177.

**Isom, B.G. 1969.** The mussel resource of the Tennessee River. Malacologia 7: 397-425.

**Isom, B.G. 1971.** Mussel fauna found in Fort Loudoun Reservoir Tennessee River, Knox County, Tennessee, in December, 1970. Malacological Review 4: 127-130.

**Isom, B.G. 1972.** Mussels in the unique Nickajack Dam construction site, Tennessee River, 1965. Malacological Review 5: 4-6.

**Jones, R.L. 1991.** Population status of endangered mussels in the Buttahatchee River, Mississippi and Alabama, Segment 2, 1990. Unpublished report, Mississippi Museum of Natural Science, Museum Technical Report 14: 36 pp.

**Keller, E.A. 1978.** Pools, riffles, and channelization. Environmental Geology 2: 119-127.

**Klippel, W.E. and P.W. Parmalee. 1979.** The naiad fauna of Lake Springfield, Illinois: an assessment after two decades. The Nautilus 94: 189-197.

**Kunz, G.F. and C.H. Stevenson. 1908.** The Book of the Pearl. Century Co., New York. 548 pp.

**Layzer, J.B., Gordon, M.E., and R.M. Anderson. 1993.** Mussels: the forgotten fauna of regulated rivers. A case study of the Caney Fork River. Regulated Rivers: Research & Management 8: 63-71.

**Lee, R.D. 1973.** Allegheny River dredging study, June 1972 - July 1973. Unpublished report, Pennsylvania Fish Commission, Harrisburg.

**Lewandowski, K. and A. Stanczykowska. 1975.** The occurrence and role of bivalves of the family Unionidae in Mikolajskie Lake. Ekologia Polska 23: 317-334.

**Libois, R.M. and C. Hallet-Libois. 1987.** The unionid mussels (Mollusca, Bivalvia) of the Belgian upper River Meuse: an assessment of the impact of hydraulic works on the river water self-purification. Biological Conservation 42: 115-132.

**Ligon, F.K., Dietrich, W.E., and W.J. Trush. 1995.** Downstream ecological effects of dams. BioScience 45: 183-192.

**Loar, J.M., Dye, L.L., Turner, R.R., and S.G. Hildebrand. 1980.** Analysis of environmental issues related to small-scale hydroelectric development. I. Dredging. Unpublished report, Oak Ridge National Laboratory, Environmental Sciences Division Publication 1565. 134 pp.

**Lydeard, C. and R.L. Mayden. 1995**. A diverse and endangered aquatic ecosystem of the southeast United States. Conservation Biology 9: 800-805.

**McMurray, S.E., Schuster, G.A., and B.A. Ramey. 1999.** Recruitment in a freshwater unionid (Mollusca:Bivalvia) community downstream of Cave Run Lake in the Licking River, Kentucky. American Malacological Bulletin 15: 57-63.

**Marking, L.L. 1979.** Effects of burial by dredge spoil on mussels. US Fish & Wildlife Service Research Information Bulletin 79-17: 1.

**Marzolf, G.R. 1978.** The potential effects of clearing and snagging on stream ecosystems. Unpublished report, US Fish and Wildlife Service, FWS/OBS-78/14, Washington DC.

**Miller, A.C. and B.S. Payne. 1992.** Characterization of a freshwater mussel (Unionidae) community immediately downriver of Kentucky Lock and Dam in the Tennessee River. Transactions of the Kentucky Academy of Science 53: 154-161.

**Miller, A.C. and B.S. Payne. 1995.** An analysis of freshwater mussels (Unionidae) in the upper Ohio River near Huntington, West Virginia: 1993 studies. Unpublished report, US Army Corps of Engineers, Waterways Experiment Station, Technical Report EL-95-264 pp.

**Morris, T.J. and L.D. Corkum. 1996.** Assemblage structure of freshwater mussels (Bivalvia: Unionidae) in rivers with grassy and forested riparian zones. Journal of the North American Benthological Society 15: 576-586.

**Mueller, J.E. 1975.** Restless River. Texas Western Press, El Paso. 153 pp.

**Nagel, K.-O. 1987.** Untersuchungen an einer Najadenpopulation (Bivalvia:Unionidae) in einem Baggersee bei Kassel (Nordhessen). Philippia 5: 383-395.

**Nagel, K.-O. 1992.** Das Schalenwachstum dreier Muschelarten (Bivalvia: Unionidae) in der Schwalm, einem nordhessischen Mittelgebirgsfluß. Decheniana 145: 165-176.

**Neck, R.W. and R.G. Howells. 1994.** Status survey of Texas heelsplitter, *Potamilus amphichaenus* (Frierson, 1898). Unpublished report, Texas Parks and Wildlife Department, Resource Protection Division and Inland Fisheries Division, Austin. 47 pp.

**Neel, J.K. 1963.** Impact of Reservoirs. Pages 575-593. *In*: Frey, D.G. (editor): Limnology in North America. University of Wisconsin Press, Madison. 734 pp.

**Nelson, K.L. 1993.** Instream sand and gravel mining. Pages 189-196, *In*: C.F. Bryan and D.A. Rutherford (editors), Impacts on warmwater streams: guidelines for evaluation. Southern Division, American Fisheries Society, Little Rock, Arkansas. 285 pp.

**Nelson, R.W., Dwyer, J.R., and W.E. Greenberg. 1987.** Regulated flushing in a gravel-bed river for channel habitat maintenance: a Trinity River case study. Environmental Management 11: 479-493.

**Ortmann, A.E. 1918.** The nayades (freshwater mussels) of the Upper Tennessee drainage. With notes on synonymy and distrbution. Proceedings of the American Philosophical Society 57: 521-626.

**Ortmann, A.E. 1925.** The naiad-fauna of the Tennessee River system below Walden Gorge. American Midland Naturalist 9(7): 321-372.

**Osborne, L.L. and D.A. Kovacic. 1993.** Riparian vegetated buffer strips in water-quality restoration and stream management. Freshwater Biology 29: 243-258.

**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: 81-93.

**Parmalee, P.W., Klippel, W.E., and A.E. Bogan. 1982.** Aboriginal and modern freshwater mussel assemblages (Pelecypoda:Unionidae) from the Chickamauga Reservoir, Tennessee. Brimleyana 8:75-90.

**Patric, J.H. and G.M. Aubertin. 1977.** Long-term effects of repeated logging on an Appalachian stream. Journal of Forestry 75: 492-494.

**Pennington, C.H. and F.D. Shields. 1993.** Dikes and levees. Pages 115-134, *In* C. F. Bryan and D.A. Rutherford (editors), Impacts on warmwater streams: guidelines for evaluation. Southern Division, American Fisheries Society, Little Rock, Arkansas. 285 pp.

**Petts, G.E. 1984.** Impounded rivers, perspectives for ecological management. John Wiley and Sons, New York.

**Reinhart, G.F. 1937.** Rectification of the Rio Grande in the El Paso/Juarez valley. American Journal of International Law 31: 44-54.

**Riggs, C.D. and G.R. Webb. 1956.** The mussel population of an area of loamy-sand bottom of Lake Texoma. American Midland Naturalist 56: 197-203.

**Rutherford, D.A., Echelle, A.A. and O.E. Maughan. 1992.** Drainage-wide effects of timber harvesting on the structure of stream fish assemblages in southeastern Oklahoma. Transactions of the American Fisheries Society 121:716-728.

**Schmidt, J.E. 1986.** Notes on the historic and present naiad fauna of the Caney Fork River, central Tennessee. American Malacological Bulletin (4): 117.

**Schuster, G.A., Butler, R.S., and D.H. Stansbery. 1989.** A survey of the unionids (Bivalvia: Unionidae) of Buck Creek, Pulaski County, Kentucky. Transactions of the Kentucky Academy of Science 50: 79-85.

**Semenova, M.N., Karpytcheva, L.A., Voloshenko, K.K., and B.F. Bugaev. 1992.** Comparative study of shell growth rate in freshwater pearl mussel *Margaritifera margaritifera* (Bivalvia, Margaritiferidae) from different rivers. Zoologicheskii Zhurnal 71(5): 19-27.

**Sickel, J.B. and C.C. Chandler. 1996.** Unionid fauna of the lower Cumberalnd River from Barkley Dam to the Ohio River, Kentucky (Mollusca: Bivalvia:Unionidae). Transactions of the Kentucky Academy of Science 57: 33-46.

**Simpson, P.W., Newman, J.R., Keirn, M.A., Matter, R.M., and P.A. Guthrie. 1982.** Manual of stream channelization impacts on fish and wildlife. Unpublished report, US Fish and Wildlife Service FWS/OBS-82/24.

**Smith, P.W. 1968.** An assessment of changes in the fish fauna of two Illinois rivers and its bearing on their future. Transactions of the Illinois State Academy of Science 61: 31-45.

**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 76: 3-14.

**Sparks, R.E. 1995.** Need for ecosystem management of large rivers and their floodplains. BioScience 45: 168-182.

**Stansbery, D.H. 1973.** Dams and the extinction of aquatic life. Garden Club of America Bulletin 61: 43-46.

**Stuebner, S. 1993.** Salmon advocates say the quiet slaughter continues. High Country News 25(10): 1.

**Suloway, L., Suloway, J.J., 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: 79-90.

**Swink, W.D. and K.E. Jacobs. 1983.** Influence of a Kentucky flood-control reservoir on the tailwater and headwater fish populations. North American Journal of Fisheries Management 3: 197-203.

**Trautman, M.B. and D.K. Gartman. 1974.** Re-evaluation of the effects of man-made modifications on Gordon Creek between 1887 and 1973 and especially as regards its fish fauna. Ohio Journal of Science 74: 162-173.

**Unkenholz, D.G. 1986.** Effects of dams and other habitat alterations on paddlefish sport fisheries. Pages 54-61 *In* J.G. Dillard, L.K. Graham, and T.R. Russell (editors), The paddlefish: status, management, and propagation. North Central Division, American Fisheries Society, Special Publication 7.

**Valovirta, I. 1990.** Conservation of *Margaritifera margaritifera* in Finland. Council of Europe Environmental Encounters Series 10: 59-63.

**van der Schalie, H. 1938.** Contributing factors in the depletion of naiades in eastern United States. Basteria 3: 51-57.

**Van Hassel, J.H., Ney, J.J., and D.J. Garling. 1980.** Heavy metals in a stream ecosystem at sites near highways. Transactions of the American Fisheries Society 109: 636-643.

**Watters, G.T. 1988.** The naiad fauna of selected streams in Ohio. I. Stillwater River of Miami River. II. Stream systems of south central Ohio from the Little Miami River to the Hocking River, excluding the Scioto River proper. Unpublished report to the Division of Wildlife, Ohio Department of Natural Resources, Columbus 440 pp.

**Watters, G.T. 1996.** Small dams as barriers to freshwater mussels (Bivalvia, Unionoida) and their hosts. Biological Conservation 75:79-85.

**Watters, G.T. and H.L. Dunn. 1995.** The Unionidae of the lower Muskingum River (RM 34.1-0), Ohio, USA. Walkerana 7: 225-263.

**Wesche, T.A. 1985.** Stream channel modifications and reclamation structures to enhance fish habitat. Pages 103-163, *In* J.A. Gore, (editor), The Restoration of Rivers and Streams, Butterworth Publications, Stoneham, Massachusetts.

**Williams, J.D., Fuller, S.L.H., 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.

**Winger, P.V., Schultz, D.P., and W.W. Johnson. 1985.** Contamination from battery salvage operations on the Chipola River, Florida. Proceedings of the Annual Conference of the Southeastern Association of Fish and Wildlife Agencies 39: 139-145.

**Wolcott, L.T. and R.J. Neves. 1994.** Survey of the freshwater mussel fauna of the Powell River, Virginia. Banisteria 3: 3-14.

**Woodward, F.R. 1990.** Problems in the control of exploitation of freshwater mussels, with particular reference to *Margaritifera*. Council of Europe Environmental Encounters Series 10: 52-54.

**Yeager, B.L. 1993.** Dams. Pages 57-113, *In* C.F. Bryan, and D.A. Rutherford (editors), Impacts on warmwater streams: guidelines for evaluation. Southern Division, American Fisheries Society, Little Rock, Arkansas. 285 pp.

**Yeager, B.L. 1994.** Impacts of reservoirs on the aquatic environment of regulated rivers. Unpublished report, Tennessee Valley Authority, Resource Group Water Management, TVA/WR-93/1. 109 pp.

**Yokley, P. and C.H. Gooch. 1976.** The effect of gravel dredging on reservoir primary production, invertebrate production, and mussel production, July 1, 1974 - June 30, 1976. Unpublished report, Tennessee Wildlife Resources Agency Technical Report 76-56. 32 pp.