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The Construction, Aesthetics, and Effects of Lakeshore Development: A Literature Review

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Abstract

We review 276 books, theses, and articles published during 1919-98 on the construction, aesthetics, and ecological effects of lakeside riprap, seawalls, piers and other dockage, bottom fabrics, and woody debris removal. We also review the public trust doctrine, Wisconsin case law, and state regulation of lakeshores.

Riprap is easier to construct and less harmful to aquatic life than seawalls of rock, steel, wood, or concrete. Poor design and subsequent neglect of seawalls allow erosion to continue. Bioengineering—integrating plants with technology—can replace seawalls for natural looking lakeshores.

Many riparians prefer vegetation to development along shore, yet tolerate unobtrusive homes, piers, and boathouses. Although vegetation can screen shoreline structures and enhance lakeshore beauty, riparians still clear plants to boat, swim, and view the shore.

Riprap and vertical seawalls destroy rushes *(Juncus),* sedges *(Carex),* bulrushes *(Scirpus),* and spikerushes *(Eleocharis)* that grow at the water's edge as well as pondweeds *(Potamogeton)* and native watermilfoils *(Myriophyllum)* that grow close inshore. These plants provide food and cover for macroscopic invertebrates, such as snails (Gastropoda) and midge larvae (Diptera), that are eaten by fishes, frogs, and ducks. Vertical seawalls also expose basking snakes and turtles to mammalian predators and keep frogs, ducklings, and turtles from leaving water.

Burlap or coir blankets can retard erosion control on steep slopes yet allow underlying seeds to sprout before the mesh decays. Synthetic blankets, liners, and screens can form beaches and boating lanes but become buried in sediment if not removed for cleaning.

Course woody debris—logs, limbs, and brush toppled by winds, beavers (*Castor canadensis* Kuhl), and people—provides food and shelter for fishes, frogs, waterbirds, and mammals as well as invertebrates like clams and bryozoans. Snakes and turtles use floating and overhanging logs as basking sites; waterfowl use the debris as brooding sites. Clearing brush and trees from shore and pulling woody debris from shallow water can increase shore erosion and expose amphibians, reptiles, and waterbirds to mammalian predators.

Each new lakeshore structure adds to the cumulative effects of neighboring structures. Piers add to boating pressure; seawalls subtract from wildlife habitat. Such habitat loss becomes critical when lakeshore vegetation is scarce. But some structures can improve habitat: Riprap adds invertebrate habitat along waveswept shores; bottom fabrics improve edge effect by channeling expansive weed beds.

Lakeshore development should be guided by habitat protection and habitat restoration plans to define goals, evaluate options, and coordinate development. Lake classification can define boating and development levels appropriate for different waters, though limiting development on some lakes can increase development on others. A broader and more creative educational outreach is needed to inform people, especially children, on the value of plant habitat and the role of lake management.

Contents

Introduction

Wisconsin lakeshores are subject to increasing development as more people visit lakes to fish, boat, and buy lakefront property. Over 4 million people visit Wisconsin lakes each year, more than one-fourth of them to fish (Klessig 1985). Since 1970, boat registrations in Wisconsin have increased 60% to 0.5 million (Penaloza 1991), while the state's population grew at nearly 4% per decade (U. S. Bureau of the Census 1997).

This growing demand for water and shore space poses a challenge to natural resource managers: how to keep abreast of an expanding scientific literature and still provide sound stewardship of lakeshores. Managers today must understand the physical, chemical, and biological processes at work along lakeshores. They must also know the legal basis for regulating shorelines and the concerns of waterfront landowners (riparians) about lakeshore aesthetics. They shall need to integrate this knowledge at population, community, and ecosystem levels and apply it to local, watershed, and ecoregion problems.

But does this expanding knowledge meet management responsibilities, or do gaps exist in our understanding that must be filled through further research?

To help managers fulfill these responsibilities, we evaluate literature on the construction, aesthetics, and ecological effects of lakeshore development. We cover bouldery riprap, seawalls (concrete, steel, stone, and plank walls), piers and other dockage, bottom fabrics (natural or synthetic blankets, liners, screens, and rolls), and woody debris removal (submerged or overhanging logs, trees, brush, leaves, and trimmings). We mainly review professional journals and technical books—peer reviewed to improve validity and reliability.

We aim to show (1) how these structures could directly or indirectly affect macroscopic plants and invertebrates, (2) how such changes in turn could affect fishes and other vertebrates, (3) how lakeshore planning combined with bioengineering can minimize ecological harm, and (4) what management and research efforts are needed to improve the Department of Natural Resources (DNR) stewardship of lakeshores.

We want managers and riparians to read on. So we use common words, define technical terms, and stick to familiar American units. We also reveal limitations to published studies and discuss promising new approaches, such as aquascaping and bioengineering. We hope lake managers and zoning authorities—public stewards of our lakeshores—will learn more about control options and lakeshore planning. And we hope riparians—private stewards of these shores—will learn more about lake management and waterfront responsibilities.

Legal Basis for Shoreline Regulation

Shoreline regulation evolved from legal challenges and permit decisions known collectively as the *public trust doctrine*, a body of laws establishing public rights in navigable waters. Rooted in Roman and English civil law, including the Magna Carta of 1215, the public trust doctrine is not one doctrine so much as 51 doctrines (Wolz 1992), each differing by state and from the federal government's doctrine (Ingram and Oggins 1992).

The public trust doctrine in Wisconsin was incorporated into the state constitution of 1848 (section 1 of article IX), from language in the Northwest Ordinance of 1787, and evolved from statutes issued after 1852 (Scott 1965, Quick 1994). The Wisconsin legislature delegated the day-to-day administration of the public trust doctrine to the Pubic Service Commission (PSC) and more recently to the Department of Natural Resources, Department of Justice, and district attorneys.

PHOTO: SANDY ENGEL

Bouldery riprap and a lakefront home with shallow setback for a view corridor of Upper Gresham Lake, Vilas County, Wisconsin.

PHOTO: SANDY ENGEL

Bouldery riprap and an overhanging deck leaving trees but little ground cover along a windy shore of Bass Lake, Oconto County, Wisconsin.

Wisconsin holds *navigable waters* in trust for all its citizens. At first, waters were judged "navigable in fact" if they could float a saw log (*Olson v. Merrill*, 42 Wis. 203, 1877). Now these waters must float a "boat, skiff or canoe of the shallowest draft" for at least part of each year (*DeGayner and Co. Inc. v. DNR*, 70 Wis. 2d 936, 1975). The state has an "affirmative duty" to keep navigable waters safe from water pollution (*Reuter v. DNR*, 43 Wis. 2d 272, 1969) and open to public fishing (*Willow River Club v. Wade*, 100 Wis. 86, 1898), hunting (*Diana Shooting Club v. Husting*, 156 Wis. 261, 1914), and other recreational uses such as enjoyment of scenic beauty (*Muench v. PSC*, 261 Wis. 492, 1952).

The Wisconsin Supreme Court has recognized "the importance of considering the 'cumulative impacts' of gradual intrusions into navigable waters" and has admonished the DNR to consider such effects (*Hixon v. PSC*, 32 Wis. 2d 608 and 631–32, 146 N.W. 2d 589, 1966). The Wisconsin Second District Court of Appeals has also reaffirmed the importance of considering cumulative effects: Adding even an extra boat slip to a multiple pier complex "allows one more boat which inevitably risks further damage to the environment and impairs the public's interest in the lakes" (*Sterlingworth Condominium Assoc. Inc. v. DNR*, 205 Wis. 2d 702, Circuit Appeals, 1996). Wisconsin's Environmental Policy Act (s. 1.11, Wis. Stats.; s. NR 150.22[2], Wis. Adm. Code) likewise urges the state to consider cumulative effects in permit decisions. The DNR, consequently, may deny permits to construct piers or other structures previously allowed on the same lakeshore.

The cumulative effects of lakeshore development can differ among lakes and be hard to recognize. Clearing a lakeside marsh, for example, could destroy spawning habitat not only for fishes but also for little-noticed frogs and invertebrates. Decisions on potential cumulative effects require specific knowledge of a lake and its *sustainability* (the limit of development before irreparable ecosystem harm).

Wisconsin law distinguishes *riparian (private) rights* from public ones (Scott 1965). Riparians have the right to "reasonable use" of shorelines for navigation, recreation, and scenic beauty. For example, riparians have exclusive use of unnavigable waters on their land and access to the shore of navigable waters bordering their property. Some riparian rights are subject to state regulation, such as the right to build piers and erosion control structures at the shore. Riparians can also elect to limit their rights, sometimes for tax benefits, by placing their land in a conservation easement or land trust that excludes future development. When private rights conflict with public rights to navigable waters, compromises can be reached: Riparians may build a pier though not longer than necessary. When conflicts cannot be resolved, riparian rights become secondary to the public interest (Quick 1994).

Wisconsin's public trust doctrine is administered through legislative statutes (Stats.) and natural resources (NR) administrative codes—noted by chapter (c.) or section within chapters (s.)—as well as internal guidance and manual codes. They define the DNR's authority to regulate such activities as fishing and hunting (c. 29, Wis. Stats.; c. NR 10–26, Wis. Adm. Code), riprap and seawall construction along shore (c. 30, Wis. Stats.), shoreland zoning (s. 59.97, Wis. Stats.; c. NR 115 and NR 117, Wis. Adm. Code), floodplain zoning (s. 87.30, Wis. Stats.; c. NR 116, Wis. Adm. Code), wetland use (c. NR 103, Wis. Adm. Code), and herbicide control of aquatic plants (c. NR 107, Wis. Adm. Code).

Chapter 30 of the Wisconsin Statutes requires a permit or special authorization to place such "structures" as riprap, seawalls, docking facilities, bottom fabrics, and fishing cribs below the *ordinary high water mark* (a distinct mark left on a bank or shore by the presence or action of water) of a navigable waterway. A newspaper notice and 30-day period for public review and response are required of some permit applications (s. 30.12[2] and 30.19, Wis. Stats.) though usually not for installing bottom fabrics or building riprap, seawalls, piers, ramps, and fishing cribs. Chapter 30 also requires cut plants to be removed from navigable waters (s. 30.125, Wis. Stats.); exempts piers and swimming rafts from permit under most circumstances (s. 30.13, Wis. Stats.); prohibits navigational obstructions (ss. 30.15–16, Wis. Stats.); and requires a permit for diverting water (s. 30.18, Wis. Stats.), grading or filling more than 10,000 ft^2 of bank (s. 30.19, Wis. Stats.), and dredging materials below the ordinary high water mark of a waterbody (s. 30.20, Wis. Stats.).

PHOTO: SANDY ENGEL

A seawall of mortared stone protecting a lakeside lawn on Bass Lake, Oconto County, Wisconsin.

Seasonal and permanent piers in Wisconsin are regulated by the DNR (ss. 30.12–13, Wis. Stats.; c. NR 326, Wis. Adm. Code) and other agencies. The DNR's "Program guidance to riparian berths and moorings" (G. E. Meyer, DNR, memo to district directors, 19 Dec. 1991) explains sections 30. 12–13 of the Wisconsin Statutes. Although not law, this "pier guidance" has been affirmed by Wisconsin's Second District Court of Appeals "as reasonable" and not "arbitrary or capricious" in planning the number, location, and construction of piers (*Sterlingworth Condominium Assoc. Inc. v. DNR*, 205 Wis. 2d 702, Circuit Appeals, 1996).

Riparians may construct a pier or wharf for boating, so long as the structures do not exceed "reasonable use" of the property. Piers owned in fee title by riparians require no state permit if (1) placed and maintained by the waterfront property owner; (2) confined to the owner's riparian zone (below the ordinary high water mark); (3) not obstructing navigation, encircling a waterway, or isolating a waterway; (4) not damaging to spawning fishes, beneficial plants, waterfowl nesting, lakeshore beauty, or other public interests; and (5) limited to 2 moorings (all docking facilities) for the first 50 ft of frontage plus 1 mooring for each additional 50 ft of frontage. No portion of a pier may exceed a width of 6 ft or extend offshore beyond the line of navigation (usually delimited by a water depth of 3 ft).

Other dockage must also meet "reasonable use" standards. Mooring buoys require no state permit if set within 150 ft of the ordinary high water mark. Boat shelters must comply with chapter NR 326 of the Wisconsin Administrative Code, be built without sides for a single watercraft, and require a state permit if not removed yearly between December 1 and April 1. Boathouses must be built on land, require a county permit, and may be regulated by local or county ordinances; those built over water before 1979 may remain but are subject to state repair and maintenance restrictions. Boathouses that obstruct navigation or need major repair may be denied a repair certification and ordered removed under section NR 325.12 of the Wisconsin Administrative Code.

Design and Construction of Shoreline Structures

People install a variety of shoreline structures—riprap, seawalls (revetments), piers, boathouses, and bottom fabrics—usually to retard soil erosion or improve recreation (McComas 1991). They also clear lakeshores of woody debris and live trees to improve boating, swimming, and viewing the lake surface.

Riprap and Seawalls

The most common erosion control structure along Wisconsin lakes is *riprap* built of gravel, cobbles, boulders, rock fragments, or a combination of stones on natural or graded slopes (Figure 1). Stone riprap can be dumped, hand placed, wire enclosed, or mortared with grout, concrete slabs, or poured concrete. Gabions (stonefilled wire baskets and mattresses) can replace stone riprap on steep slopes and allow underlying seeds to sprout (Ragazzo 1997). Coir (coconut husk fiber) logs sometimes replace the heavier stone riprap to stabilize slopes (Santha 1994), though the logs must be anchored with rebar, stones, or wooden stakes (Goldsmith 1993).

Less common are *seawalls* (solid retaining walls) built of stone, wood, or metal (Figure 2). Stone walls are usually made of mortared stone or solid concrete, though interlocking synthetic blocks can replace stone for flexibility in construction and design (Nelson 1995). Wooden walls are built of vertical or horizontal planks made of cedar posts, chemically treated lumber, or railroad ties. Metal walls are made of steel sheeting fixed to wooden planks or posts, though sometimes interlocking aluminum replaces the steel. Homes and boathouses built at the water's edge can also serve as seawalls.

Riprap and seawalls hold back soil and blunt wave action, though soil can still erode between and behind the structures (McComas 1991). These structures must resist *wave height*, a function of wind speed and lake exposure (fetch), as well as *wave runup*, a function of wave height and shore slope (McComas et al. 1985). Breaking waves could overtop low or inclined seawalls, though backfilling (adding soil behind exposed wall sections) and building seawalls too high can destroy brush and trees that hide the seawalls from shore and provide wildlife habitat.

Lakeshores sometimes need to be graded for proper slope, though laying geotextile (natural fiber) filter cloth beneath riprap or staking sod can be less harmful on steep shores (Figure 1). Soils of cohesive clay, however, need less stabilization than those of porous sand or flocculent peat (McComas 1990). Wattles (lashed branches) of willow (*Salix*) or dogwood (*Cornus*) can be staked at the water's edge to dissipate wave energy (Goldsmith 1991*a*) or trenched along steep slopes for a terraced effect that retards erosion and improves rooting (Goldsmith 1991*b*). Grasses (Poaceae) and other wildflowers (forbs) take root in sediment trapped by the wattles to enhance runoff

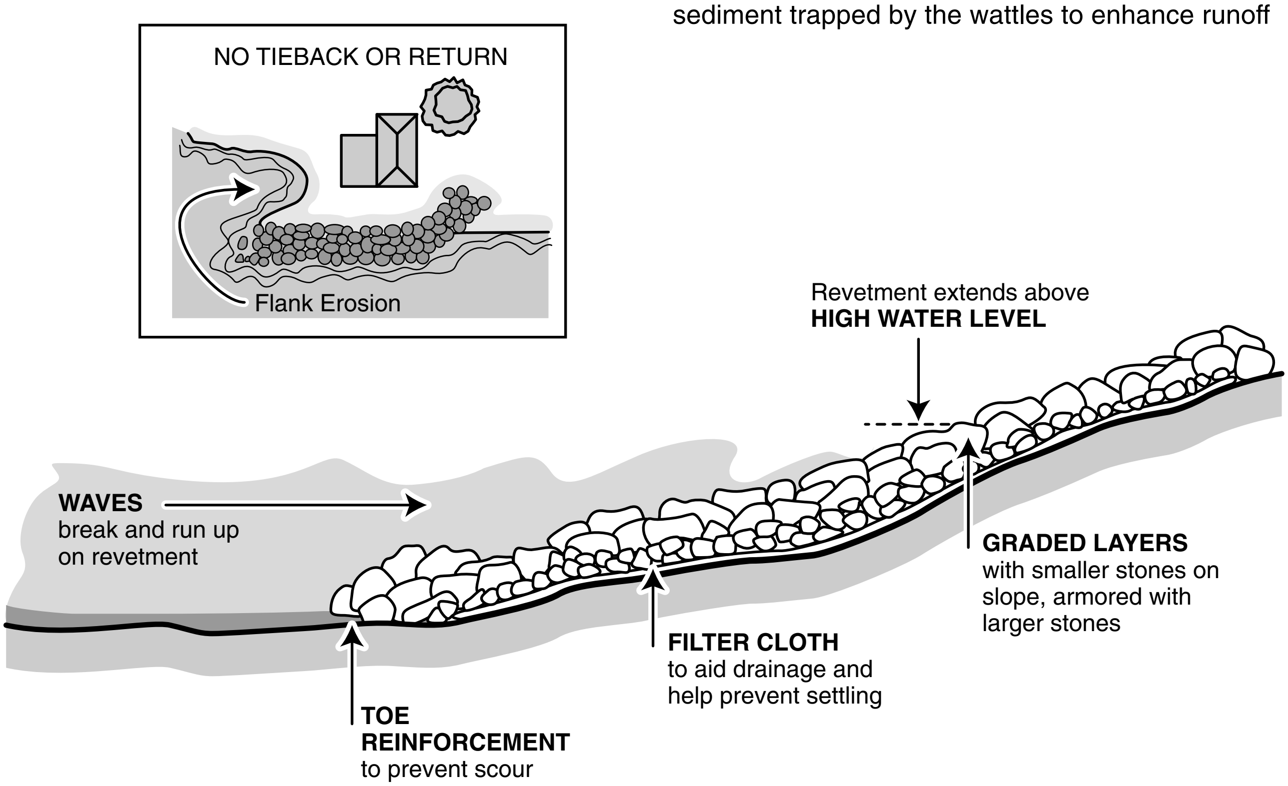


Figure 1. *Bouldery riprap diagramed to show wave action in relation to flank erosion (top) and construction layers (bottom). Adapted from Rogers, Golden and Halpern, Inc., U. S. Army Corps of Engineers (1981).*

protection and lakeshore habitat (Bentrup 1996).

Proper seawall design and construction varies with the soil, slope, and exposure of the shore. The size of riprapped stone should increase with slope and expected wave or ice action. Boulders and large rock fragments are recommended on grades (expressed as vertical to horizontal lengths) as steep as 1:3 to 1:2 (Bhowmik 1978). A base of sand and gravel over filter cloth can further stabilize the riprap (McComas et al. 1985). Cinder blocks, concrete slabs, gabions, planks, posts, and vegetation placed at the water's edge can blunt waves.

Wave-washed shores sometimes need protection with toes or wing dams that stretch to a water depth of about 1.5 times wave height (McComas 1991). Acting as speed bumps to dampen water turbulence, these breakwaters are built of boulders, steel, stones, timbers, or interlocking bags of concrete (Oertel 1995). Rock riprap can also protect the base of seawalls and looks more natural than steel or concrete.

Soil erosion and siltation temporarily increase during lakeside construction (McComas 1991) as do noise, vibration, and air pollution from machinery. When plant cover is removed early in construction, soil washes off slopes during heavy rain or snowmelt. Trucks then form ruts that channel the runoff into adjoining lakes. Grading, dumping, and backfilling soil on shore causes sand and gravel to slough onto the base of structures, unless hay bales or silt (erosion) fences are used (Gray and Sotir 1996). Water turbidity increases for a while, depending on wave action, soil density, and particle size: Clay settles more slowly than silt, silt settles more slowly than sand, and all particles settle more slowly on windy shores than on calm ones (Bhowmik 1978).

Erosion can continue long after riprap and seawall construction are completed, if the top, flanks, and base of these structures are not protected from ice, rain, snow, wind, and waves; a blanket, screen, or sand filter behind these structures reduces erosion from water seepage (McComas 1990, 1991). Even with these precautions, shoreline structures must be maintained to minimize erosion and avoid interference with navigation.

Construction failures result from (1) inappropriate site, (2) inadequate design or materials, and (3) poor coordination with neighboring structures (Lichtkoppler and Batz 1991). Construction failures are common on exposed sites. Riprap and seawalls can weaken from ice push (ice shove) during winter, ice heave and frost action in late winter, ice jam at ice-out, and wind or wave action during ice-free months (Barnes 1928). Frost action, ice heave, or wind and wave action can loosen stones at the base to cause collapse (slumping) of higher materials.

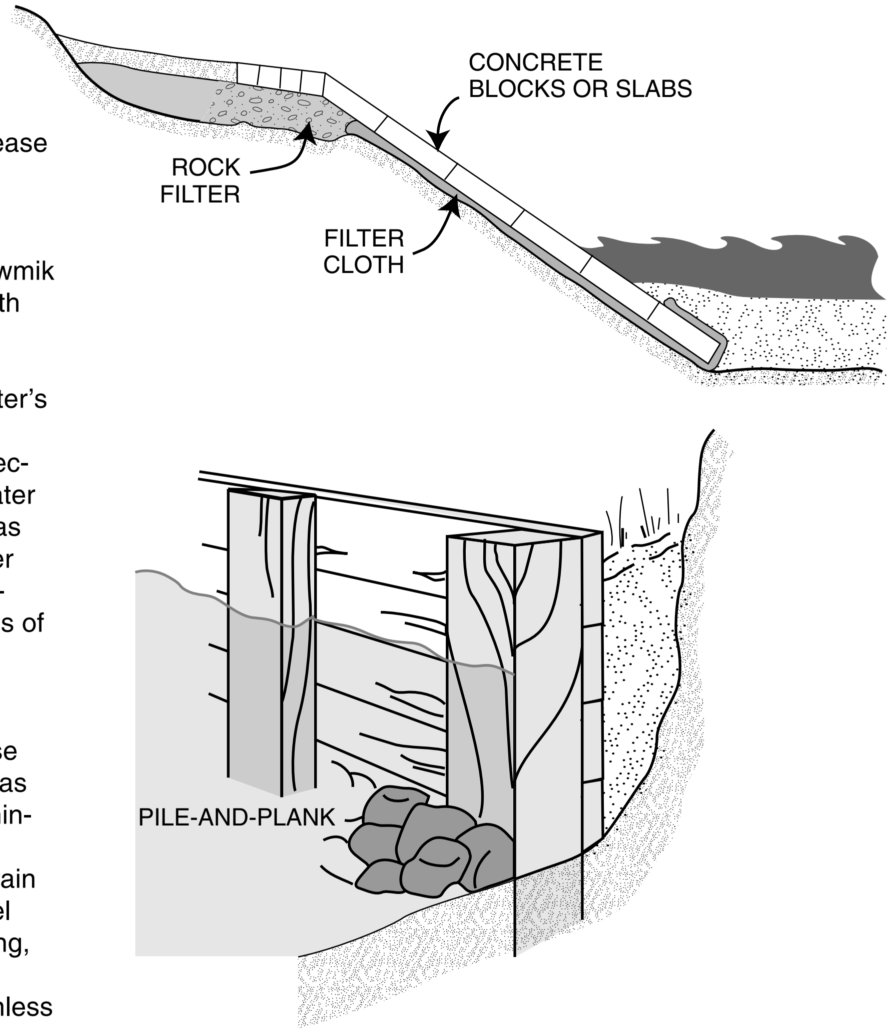


Figure 2. *Solid retaining walls (seawalls) built of concrete (top) or wood (bottom). Adpated from Rogers, Golden and Halpern, Inc., U. S. Army Corps of Engineers (1981).*

Skimping on initial construction, by using poor materials and improper construction, can lead to costly upkeep, repair, redesign, and replacement (McComas et al. 1985). Not stabilizing bank soil on grades steeper than 1:4 can mean expensive regrading later. Eroded soil can reach nearby waters unless silt fences—plastic mesh resembling snow fencing (Murphy 1995)—are used. Riprap and seawalls can collapse from improper bed or

PHOTO: SANDY ENGEL

A mortared stone seawall developing some crevices for invertebrates to colonize on Upper Gresham Lake, Vilas County, Wisconsin.

overtopping with fill. Annual maintenance costs also increase from wear on structures by ice damage, storm damage, daily winds and waves, and flank erosion from neighboring structures.

Not coordinating development with nearby structures can increase erosion and water damage to unprotected property. A succession of seawalls can deflect wind-driven waves and intensify currents at downdrift sites, causing beach cutting and soil loss between structures. The eroded sediment can drift (focus) into deep water (Blais and Kalff 1995). Increased water turbidity, disruption of fish spawning, and invasion sites for exotic plants also result from sediment erosion (Engel and Nichols 1994).

Piers and Related Dockage

Piers, wharves, mooring buoys, and a variety of boat storage facilities appear each spring on lakeshores. Boats are docked to single or multiple *piers* built on floats or pilings extending offshore, *wharves* built on gravel and stone along shore, or *mooring buoys* anchored offshore. Permanent piers built to withstand ice damage are giving way to seasonal piers with removable pilings and decks for water level changes and winter storage. Most seasonal piers come in 4-ft sections made of wood, aluminum, or encased polystyrene that extend on steel pilings straight from shore or bend offshore into a T- or inverted L-shape. Some seasonal piers float on tires or drums; others come on wheels for rolling and unrolling at the shore. Piers on muddy shores may need log-and-stone cribs for support.

When not in use, boats can be stored on vertical or cantilevered *lifts* (boat hoists), built with a winch and pulley system on a steel or aluminum frame set beside a pier, under a boat shelter, or in a boathouse; lifts beside piers often bear a canvas or vinyl canopy. Boats are also stored in canopied *shelters* built of steel or aluminum siding over water, or in walled *boathouses* (boat garages when attached to homes) built of brick, stone, or wood. In Wisconsin, dry boathouses built on shore are slowly replacing wet boathouses built years ago over water.

Bottom Fabrics

Bottom fabrics (bottom barriers) offer an alternative to chemical herbicides and mechanical plant harvesting to retard shore erosion and create plant-free areas for boating, swimming, or wading (Cooke et al. 1993). New fabrics unroll as *blankets* (interwoven mats) or *liners* (solid sheets) and are made of natural or synthetic fibers that are interwoven or spunbonded. Natural (geotextile) fibers that decompose in water are made of burlap, coir, jute, or straw; synthetic fibers that turn brittle or decay in sunlight are made of nylon, polyethylene, polypropylene, polyvinyl chloride, rubber, or a combination of petroleum products (Quackenbush 1967, Kumar and Jedlicka 1973, Gerber 1981, Santha 1994).

Bottom fabrics also unroll as *screens* (fiber mesh) made of burlap (Jones and Cooke 1984), coir (Goldsmith 1993, Santha 1994), or fiberglass (Engel 1984). Coir has been pressed into biodegradable logs for terracing steep slopes (Goldsmith 1993). Unlike most blankets and liners, the screens and logs can be easily removed: the screens for cleaning and the logs for relocating.

Most blankets and liners are nearly as dense as water (specific gravity of 0.95–1.30) and need a covering of sand, brick, or gravel to avoid shifting from wave disturbance and gas ballooning (Gunnison and Barko 1992). Fiberglass screens of 0.0015-inch^2 (1-mm^2) mesh, however, are much denser than water (specific gravity of 2.50) and can be anchored to the lake bed with only a border of stones or rebar (concrete-reinforcing steel rods); this avoids a covering of sand, brick, or gravel that would make the screens hard to remove for cleaning (Mayer 1978, Perkins et al. 1980). Burlap blankets must also be firmly anchored but decay in a few years (Jones and Cooke 1984). Coir blankets and logs decay within 5–10 years, depending on fiber grade, but they last long enough for a plant cover to form and stabilize the shore (Santha 1994, Gray and Sotir 1996).

Most fabrics can be installed during the growing season though are easier to apply in winter or spring before plants sprout. All require a permit under chapter 30 of the Wisconsin Statutes and may need to meet other statutes or administrative codes. Some people find installing fiberglass screens to be bothersome and thus are tempted not to remove them each year as required.

Staked on steep shores, erosion control blankets can retard runoff and soil slumping when used beneath riprap or native plantings. A cover of native wildflowers sprouting from seeds beneath decaying blankets looks pleasing, needs little care, and provides food for butterflies, hummingbirds (Trochilidae), and songbirds (Passeriformes) as well as ground cover for small mammals (Howland 1996). Newly planted shores, however, may need temporary fencing to keep out carp, turtles, crayfish, and other herbivores (Smart et al. 1998).

Anchored to the lake bed, blankets and liners block 100% of sunlight striking them (Cooke 1980, Cooke and Gorman 1980), whereas screens block 40–50% of the light and thus only partly shade underlying foliage (Perkins et al. 1980). Screens firmly anchored to the bottom, however, prevent new growth and encourage microbial decomposition of the shaded foliage (Perkins et al. 1980). Fiberglass screens should be installed in spring and removed in fall for cleaning, whereas sand-covered blankets and liners are intended to stay on the lake bed (Nichols et al. 1988). After several years without cleaning, however, these fabrics support as much plant growth as adjacent uncovered sites (Engel 1984). Burlap decomposes after a few seasons (Jones and Cooke 1984) and must be reapplied or the site planted before weeds grow.

PHOTO: SANDY ENGEL

A wooden seawall built of horizontal railroad ties beside a sectional pier on Upper Gresham Lake, Vilas County, Wisconsin.

Woody Debris

Trees, shrubs, and their fragments form woody debris on land or in water. Usually dead, the debris in water is classified by size as fine or coarse.

Fine woody debris comprises small plant matter: ash, twigs, leaves, sawdust, and bark fragments that wash or blow into water (Gasith and Hasler 1976). The debris forms when larger wood decays or breaks apart. In water, the debris either sinks or washes onto storm beaches. Decomposition of bark, twigs, and leaves varies with plant species (Gasith and Lawacz 1976) and increases with rise in water temperature and pH (Tuchman 1993). It accelerates in late spring from shredding by macroscopic invertebrates (Cummins 1973) and digestion by fungi and bacteria (Sly 1982) until the debris, now called *detritus*, undergoes wave sorting and settles on the bottom offshore, behind wet boathouses, or in rock crevices along shore. People seldom remove fine woody debris but can deplete sources for renewing it by clearing lakeshores of whole trees and shrubs that contribute leaf litter to lakes (France and Peters 1995).

Coarse woody debris includes whole trees, fallen limbs and trunks, brush, exposed tree roots, and wood fragments at least 4 inches in diameter and 5 ft long. Tree falls and log cribs have larger but fewer spaces than brush piles. Sometimes called large woody debris, it has been classified (Murphy and Koski 1989) into particles ranging in diameter from small (4–12 inches) to medium (12–24 inches), large (24–35 inches), and very large (>35 inches).

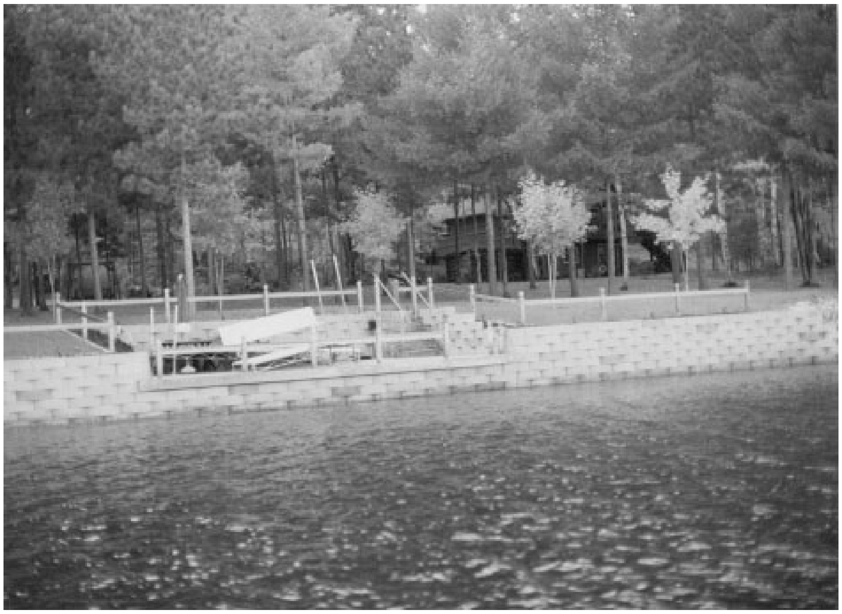


PHOTO: SANDY ENGEL

A seawall of interlocking synthetic blocks and sectional pier removed for winter storage on Bass Lake, Oconto County, Wisconsin.

Lakes in forested watersheds collect coarse woody debris when trees topple from logging, wind throws, and beaver cuts—though sometimes from ice action, inlet flow, and lightning strikes. Trees and shrubs at the water's edge can topple from ice or wave scouring; those farther upslope can topple from gully erosion (Harmon et al. 1986). Dead and diseased trees are especially prone to topple. Storm events and lake inlets can collect brush and scattered branches into deadfalls that line lake shallows. Wind and wave action fragments coarse woody debris, turning it into more degradable fine woody debris.

Aesthetics of Lakeshore Development

People differ in how they value lakeshores. Some residents relate shoreland beauty to parklike settings of scattered trees and lakeside lawns; others believe developed shorelines to be unnatural and unattractive (Macbeth 1992). Some view seawalls as improvements that raise property values; others view them as despoilments that rob wildlife of natural habitat (Wilde et al. 1992). The same person might view lakeshore vegetation favorably while angling but unfavorably while swimming.

People also differ in why they purchase waterfront property. Many riparians like to fish, hunt, swim, canoe, sailboat, or motorboat. A 1970 mail questionnaire completed by 1,183 of 1,960 waterfront property owners in Wisconsin revealed 93% of riparians enjoyed fishing, compared with 44% of the general public; but 62% of riparians listed "solitude and beauty" as the most important pleasure derived from owning waterfront property (Klessig 1973). A 1993 mail questionnaire completed by 2,334 of 14,000 subscribers to *Lake Tides*, an Extension Lake Management Program newsletter by the University of Wisconsin-Stevens Point, revealed 78% "enjoy Wisconsin's lakes mostly for their peace, quiet and natural beauty" (Korth 1994). Most of those surveyed were waterfront property owners who believed that cabins and boathouses spoil the look of the shore, yet they preferred shorelines with modest development (homes and other structures visible from shore) to shorelines with vegetation and light development (homes and other structures hidden from shore).

Plant cover affects the look of shoreline structures and how riparians envision "natural scenic beauty." Riparians ranked pictures of developed lakeshores most favorably when enough plants were present to screen shoreline structures (Steinitz and Way 1970 *in* Macbeth 1989), though some may hold a different opinion of vegetative screening if the plants block their *view corridor* (cleared path allowing a lake surface to be viewed from a dwelling back from shore).

People sometimes do not consider the look of shoreline structures when applying for chapter-30 permits. The Wisconsin Supreme Court has ruled (*Muench v. PSC.*, 261 Wis. 492, 1952; *Claflin v. DNR*, 58 Wis. 2d 182, 1972) that the public's right to "natural scenic beauty" can be the basis for the state denying a permit for lakeside construction.

Many people tolerate lakeshore development that is not too obtrusive. A study of 50 college students and 50 waterfront property owners viewing 90 color slides of 27 Wisconsin waters revealed many people tolerated homes close to shore or even close together so long as the homes remained inconspicuous (Macbeth 1992). Yet 55% of 1,097 lakefront property owners resurveyed by mail in 1970 (Klessig 1973) felt their lake was overdeveloped, having buildings on more than 6 lots per 40 acres of lake surface.

Surveys asking people to rate slides of waterfront scenes are limited by the rating system, the pictures themselves, and viewer experience. Rating systems lack equal units and a point of origin (Wohlwill 1982): A rating of 8 ("very crowded") is not necessarily four times a rating of 2 ("very uncrowded") nor will people agree on a rating of 0 ("absolutely uncrowded"). Color slides lack sound, motion, and varied angles of view—features that people integrate when looking at real lakeshores. Viewers differ in how they rate the same scene (Chenoweth 1984): A developed shore may be rated more favorably by viewers aware of shores in worse condition. Few surveyors check on how consistent their viewers rate the same scenes viewed on different days or weeks.

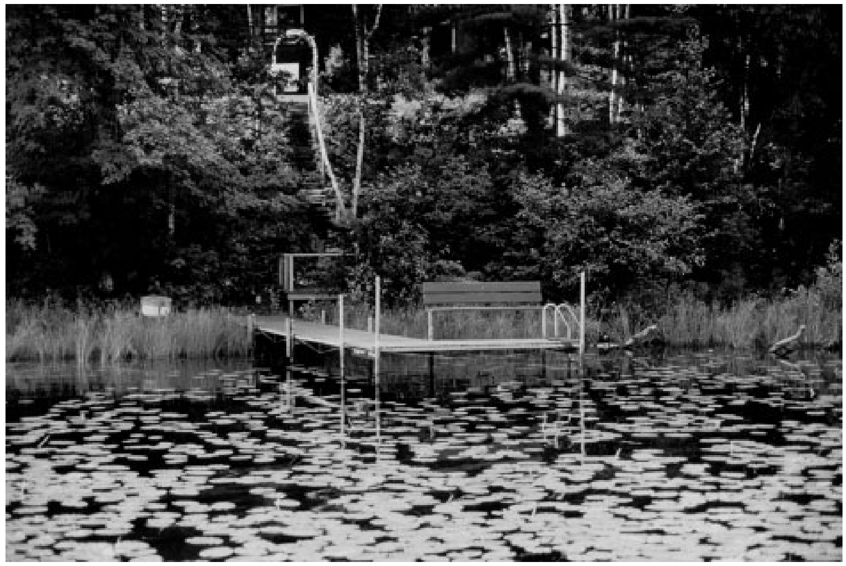


PHOTO: SANDY ENGEL

A seasonal pier surrounded by water lilies (offshore) and trees, sedges and woody debris (inshore) on Towanda Lake, Vilas County, Wisconsin.

Surveys limited to waterfront property owners ignore the opinions of other lake users. People who reside away from water may value boat landings more than lakeside homes and prefer vegetative screens to view corridors. If respondents are not picked in a random or stratified-random manner, results might not apply to a broader population of lake users and thus must be interpreted cautiously.

Many surveyors do not analyze responses by age, education, employment, income, or sex of the respondents (Wohlwill 1982). Students, for example, may view lakes as playgrounds and show less interest in "solitude and beauty" than their parents; retirees may spend more time boating and fishing than working adults.

Adding piers to a lakeshore puts more boats on the water and thus could affect boating enjoyment. A 1989 mail questionnaire completed by 39,839 of 58,800 people, most of them randomly picked from 482,336 current DNR boat licenses, revealed 93% ranked their boating experiences as "good to perfect," though 18% of them felt "moderately to extremely crowded" by other boaters (Penaloza 1991). A 1990 mail checklist of 12 possible boater problems completed by 1,592 of 2,000 boaters, randomly picked from the previous year's respondents, found 22% of boaters checked "too many other boaters on the water" and "crowding at access points" (Penaloza 1992). Discourteous boaters and too much noise, speed, and wake from boats were other problems checked by at least 15% of the respondents.

How people view lakes needs better understanding—not so much from more studies as from well-designed ones. Stratified random sampling is needed to separate age, sex, and other differences among people (Cochran 1977). Unreturned questionnaires must be followed-up to improve sample size (Penaloza 1991). And confidence limits should be calculated to estimate precision (Dillman 1978).

Ecological Effects of Lakeshore Development

Water Quality

Installing riprap and seawalls can increase siltation and nutrient enrichment of lake water through erosion and debris fall. Soil washing off construction sites contains a mix of particle sizes and textures. Silt and clay settle slowly enough to keep lake water turbid; sand and gravel settle faster but can smother fish nests. Nutrients carried by these particles can fuel algal blooms.

Water quality can continue to deteriorate long after construction. Soil washes into lakes when waves erode the base of seawalls or driving rain scours the flanks between neighboring structures (Krull 1969, Dai et al. 1977). Vertical or inclined seawalls sometimes create an undertow from breaking waves that scours the lake bed, whereas riprap usually deflects wave energy to minimize wave scour. Such water turbulence keeps silt and algae in suspension, increasing water turbidity and

PHOTO BY SANDY ENGEL

A developed shore with piers and an outboard motorboat on Hilbert Lake, Marinette County, Wisconsin.

shading tiny submersed plants like quillwort (*Isoetes*) and pipewort (*Eriocaulon*).

Water turbidity can increase indirectly when lakeshore development leads to increased boating. Passing motorboats scour sediment in shallow water and keep clay and silt in suspension, though how long these effects last depends on bottom composition and the nature and frequency of passing boats (Yousef et al. 1980). More soil enters the water when boat wakes erode unprotected shores. Sand settles within minutes of a passing boat (Garrad and Hey 1987), whereas fine organic and inorganic particles drift offshore to slowly settle in deep water (a transfer called *sediment focusing*). Nutrients in shallow sediment also rise into the water column when boats pass. Dissolved phosphorus can then stimulate growth of attached or planktonic algae (Murphy and Eaton 1983).

But studies of boating effects often do not distinguish algal blooms caused by land runoff—influenced by weather and land use patterns—from those caused by boats that stir bottom sediment and erode lakeshores (Moss 1977). Algal blooms in an English canal, for example, seemed unrelated to holiday motorboating (Hilton and Phillips 1982), though investigators did not identify sources of nutrients fueling the algae and thus could not dismiss long-term effects of motorboating.

Lakeshore development means not just more riprap, seawalls, and piers but also new houses, fertilized lawns, gravel driveways, and septic systems. During storms, for example, lawns and driveways can contribute two-thirds of the phosphorus input (loading) to lakes in residential areas (Bannerman et al. 1993), though much of this input is channeled to lakes by streets and parking lots near the lakeshore.

Lakeshore development can affect water quality in deep water. Dissolved oxygen in the hypolimnion of Michigan's Douglas Lake, for example, decreased during a 20-year span of cottage development, presumably from septic system runoff, and stayed lowest in bays ("depressions") surrounded by cottages (Lind and Dávalos-Lind 1993). Although data were corrected for water temperature and depth differences among bays, the authors compared dissolved oxygen measurements for 1922, 1971, 1982 (unusually dry), and 1992 only; data are not given for other years or variables. Differences in area, shape, and orientation of the bays can affect water quality and confound results. The lake's South Fishtail Bay, for example, lost dissolved oxygen despite few cottages along shore, because the lake water carried oxidizable organic matter from other bays into this sheltered bay. This study reveals how a few field measurements can be inadequate to establish (much less explain) a cause-and-effect relation between water quality and lakeshore development.

Clearing lakeshores of trees and shrubs robs lakes not only of woody debris (from loss of recruitment) but also of nutrients (from decay of leaf litter). Total loss of leaf litter to oligotrophic (infertile) lakes in Ontario, for example, would mean a 10–15% loss in carbon and 2–8% loss in phosphorus to lake water—enough to decrease planktonic algae (France and Peters 1995). But leaf litter is a minor nutrient source to eutrophic (fertile) lakes (Gasith and Hasler 1976), and we found no experimental evidence that loss of leaf litter affected fishes or other wildlife.

Because of a positive exponential relation between (untransformed) spring total phosphorus and summer chlorophyll *a* concentrations (Hutchinson 1957, Carlson 1977), knowledge of the watershed, flushing rate, and lake morphometry can help model total phosphorus retention (Kirchner and Dillon 1975) as well as phosphorus

A wooden pier and dry boathouse with boat ramp on Upper Gresham Lake, Vilas County, Wisconsin.

PHOTO: SANDY ENGEL

input from natural and human sources (Dillon and Rigler 1975). For example, estimated and observed total phosphorus concentrations had a positive Pearson product-moment correlation ($r^2 = 0.74$, $P < 0.05$) for 68 reservoirs in western United States (Mueller 1982). This mass-balance approach has been used to predict phosphorus input from increased cottage development (Dillon and Rigler 1975). It could provide a yardstick for judging the cumulative effects of lakeshore development.

But phosphorus adsorption (physical attraction) onto clay soils around lakes, and errors in measuring phosphorus from the atmosphere and surrounding land (Dillon et al. 1994), can mislead estimates of phosphorus input. Such models also do not consider spatial patterns of land use: Lakes receive more phosphorus from urban corridors along lake inlets and shores, where houses with septic systems and fertilized lawns are clustered and where pathways for phosphorus adsorption are short.

Yearly differences in precipitation must also be included in water quality models. Dry years reduce overland flow and the watershed area contributing to nutrient runoff. The watershed area contributing phosphorus to southern Wisconsin's Lake Mendota, for example, varied from 30% during dry years to 87% during wet ones (Soranno et al. 1996). Such variations in weather and land use patterns—leading water quality models astray—emphasize the dynamic links between land and water ecosystems (Likens and Bormann 1974).

Although aquatic communities can resist small water quality changes (Panek 1979), the cumulative effects of even small lakeshore alterations can lead to major ecosystem responses (Burns 1991). Water quality around North Carolina's Lake Waccamaw, for example, was threatened when residential development increased herbicide use, fertilizer runoff, domestic waste seepage, and drainage canal excavations (Panek 1979). Each nutrient source fueled algal blooms and thus added to the decline in water quality. In theory, dense algal blooms can shade-out underlying rooted plants in deep water and ultimately reduce the area of plant habitat for fishes, invertebrates, and diving ducks. Loss of native plants, in turn, can open the lake bed to invasions by turbidity-tolerant exotic plants. But studies of small cumulative effects from lakeshore development seldom run long enough to reveal such widespread ecosystem responses.

Physical (Woody Debris) Habitat

Woody debris constitutes *physical habitat* along lakeshores, habitat that expanded dramatically during widespread dam building and logging in Wisconsin from about 1870 to 1920 (Scott 1965, Wilson 1982). Logs were rafted across lakes and floated down rivers to sawmills and pulp mills, though lots of logs and slash were left behind. Sawdust, pieces of bark, and other fine woody debris from the logs, slash, and mill waste entered the water (Lawrie and Rahrer 1973). Banks and shores were gouged during the log drives, eroding soil into the water. The combined debris smothered fish spawning grounds (Lawrie 1978) and removed dissolved oxygen from the water upon decay.

Today, modest deposits of coarse woody debris can protect lakeshores and create invertebrate habitat. The debris blunts waves and ice action that scour the lake bed and keep seeds from sprouting or shoots from rooting. Known as *snag habitat* in streams because it traps a variety of drifting particles, the debris in lakes collects sediment and becomes coated with algae and detritus (animal and plant remains) that macroscopic invertebrates consume (Harmon et al. 1986). Woody debris thus supports high densities of midge (Chironomidae) larvae and pupae,

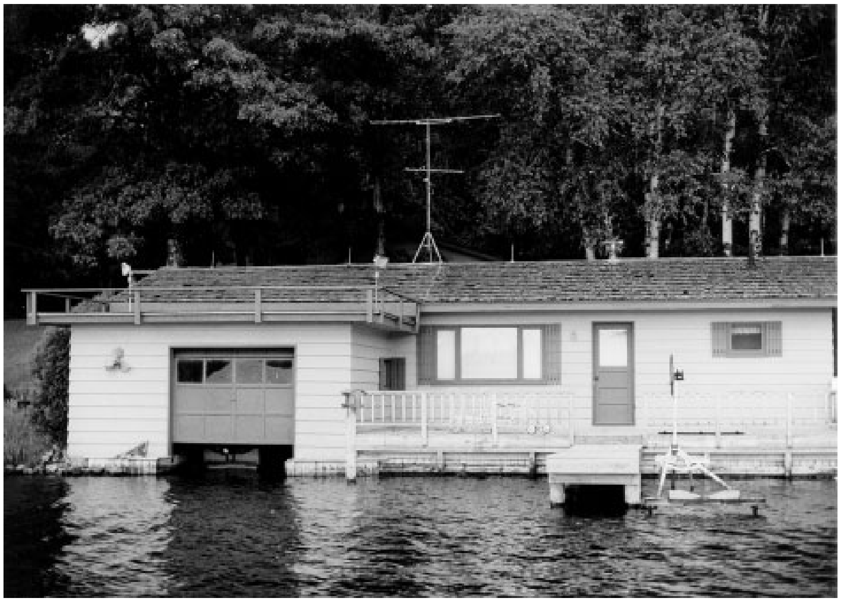


PHOTO: SANDY ENGEL

A lakefront home with wet boathouse (boat garage) and wooden pier on Upper Gresham Lake, Vilas County, Wisconsin.

including species that tunnel into bark or the heartwood of submersed pulpwood logs. Although few aquatic insects are known to eat wood (Harmon et al. 1986), their tunneling hastens decomposition by fungi (Basidiomycetes) and bacteria (McLachlan 1970).

Fish use of new tree falls and brush piles increases as algae and invertebrates colonize the debris, though prey density often remains below that on live submersed plants (McLachlan 1970). After a few years or decades, fish use of woody debris declines as the debris decays, is overgrazed by fishes, or becomes buried in sediment (Claflin 1968, Harmon et al. 1986). Such old debris can still attract suckers (Catostomidae) and minnows (Cyprinidae), though seldom pumpkinseed sunfish (*Lepomis gibbosus* [L.]) or yellow perch (*Perca flavescens* [Mitchill]) (Moring et al. 1986).

How long woody debris lasts in water depends on the size and type of wood, water temperature, and sedimentation rate (Christensen et al. 1996). Logs outlast branches, red cedars (*Juniperus virginiana* L.) outlast birches (*Betula*), and buried wood outlasts exposed wood (Harmon et al. 1986). Decay rates increase with water temperature, especially in aerobic environments. Adding new woody debris or uncovering old debris is needed to maintain prey density and fish refuge sites (Harmon et al. 1986).

Homesteading after the logging era (Wilson 1982) and recent lakeshore development have reduced woody debris in lakes through direct removal and loss of recruitment (Christensen et al. 1996). The density of coarse woody debris, for example, was negatively correlated ($r^2 = 0.71$, $P < 0.01$) with cabin density among 16 lakes in forested watersheds of northern Wisconsin and Upper Peninsula Michigan (Christensen et al. 1996). The debris averaged 893 logs/mile of total shoreline, but cabin sites had only 15% of the average woody debris density (610 logs/mile) of forested sites. Because trees grow slowly and their density within 33 ft of these lakes was positively correlated ($r^2 = 0.78$, $P < 0.01$) with woody debris density, replenishing woody debris in these developed lakes could take 200 years to reach the mean density in undeveloped lakes.

Removing woody debris by dragging submerged trees and stout logs onto shore can trample lakeshore vegetation and the nests of fishes and shorebirds. Shore erosion can increase directly from shore damage and indirectly from wind and wave action on the newly exposed shore. Water turbidity then increases from shore erosion and particles of soil and wood falling off the debris into the water. In extreme cases, stirring bottom sediments during woody debris removal can raise biochemical oxygen demand enough to deplete dissolved oxygen (Sproul and Sharpe 1968), killing sedentary invertebrates.

Habitat loss can be critical to fish and wildlife when woody debris is removed from infertile lakes with few plant beds or after riprap, seawalls, and bottom fabrics have already reduced natural habitat. This can happen when lakeshores are cleared for waterfront parks or multiple housing projects. Waves no longer blunted by woody debris could then scour the shallow bottom and keep drifting plant shoots from taking root.

But removing excess woody debris can create aquatic plant habitat by increasing sunlight penetration and warming shallow sediments. The renewed light and warmth can stimulate seed germination and growth of vegetative propagules, such as turions (dormant shoot apices), shoot fragments, underground tubers, and winter leaf-axil buds. A total of 15 aquatic plant species, for example, sprouted from lake sediment that was transferred to plastic containers and exposed to artificial light for 14 hours daily at 25°C (McFarland and Rogers 1998). Exposing lake sediment to sunlight can improve not only plant growth but also habitat for bottom-nesting sunfish and black bass (Centrarchidae).

Whether woody debris removal creates a critical habitat loss must be judged in relation to other habitat changes, though clearing lake shallows will quite likely have effects not obvious to casual observers.

Removing woody debris may require a chapter-30 permit and be subject to other statutes or administrative codes, if its removal would disturb the lake bed or destroy its historical (archaeological) value. Because sunken logs on submerged state lands belong to the state, their removal would require a permit from the Commissioners of Public Lands (s. 170.12, Wis. Stats.). Otherwise, such debris is not considered lake bed material and remains unprotected. When woody debris is scarce, however, the DNR may recommend *tree drops* (felling trees so they lean into the water).


PHOTO: SANDY ENGEL

A permanent pier built of chemically treated lumber and accessible to all anglers on Upper Gresham Lake, Vilas County, Wisconsin.

Biological (Plant) Habitat

Lakeshore vegetation includes macroscopic plants (macrophytes) that vary from spore-forming algae, ferns, and horsetails (*Equisetum*) to seed-forming conifers and angiosperms. Microscopic algae, fungi, and true mosses often grow on these larger plants as epiphytes or drift in the water near them as plankton.

As biological habitat, lakeshore vegetation forms sites for animals to feed, breed, hibernate, or seek shelter. Such habitat attracts *shore-dependent species*, like many fishes and amphibians that must spend at least part of their life along shore, and *shore-transient species*, like humans and many songbirds (Passeriformes) that inhabit the shore but can live elsewhere. Shore use ranges from brief spawning runs to year-round living, but some shore transients use the shore longer than do some shore dependents.

Habitat functioning varies with plant type. Submersed and floating-leaf plants provide (1) shore protection from breaking waves; (2) shade and cover from fish predation; (3) microhabitats for partitioning food and shelter; and (4) food and substrate for invertebrates, fishes, frogs, salamanders, turtles, and waterfowl (Engel 1990, Beauchamp et al. 1994). Emersed plants provide (1) food and building materials for waterbirds (shorebirds and waterfowl); (2) burrowing sites for small mammals; (3) basking (sunning) sites for snakes and turtles; (4) nesting, brooding, and roosting sites for waterfowl; and (5) food and shelter for frogs, salamanders, turtles, waterbirds, and mammals (Jackson 1961, Bellrose 1980, van der Valk 1989).

As *vegetative buffers*, lakeshore vegetation intercepts (biofilters) soil and dissolved nutrients moving downslope (Kent 1998). The plants also screen lakeshore development, blunt water movements, and hide animals moving between land and water. But perennial species that regrow each year from root crowns, woody stems, or evergreen shoots can store contaminants and thus integrate small cumulative effects of human disturbance.

Vegetative buffers differ in size and shape. Large buffers cover many acres and draw large animals that hunt scattered prey or defend large territories, though smaller buffers are useful for sedentary or tiny mobile animals with limited home ranges. Shallow buffers extend parallel to shore without joining uplands and stretch from less than 75 ft—vegetative strips between adjoining property—to the width of whole shorelines for maximum use as wave barriers, fish spawning sites, and raptor perches. Deep buffers extend perpendicular to shore to join uplands and work best for nutrient

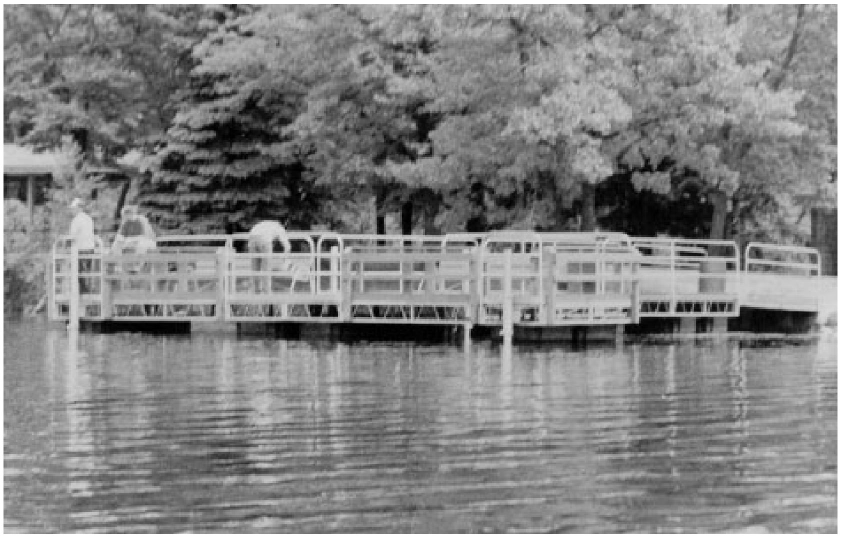


PHOTO BY SANDY ENGEL

A seasonal pier built of aluminum railings and sectional decking accessible to all anglers on Half Moon Lake, Eau Claire County, Wisconsin.

filtration, soil detention, and animal corridors.

Being immobile, aquatic rooted plants cannot flee riprap and seawall construction. Graders and front-end loaders can bury or uproot emersed plants, destroying seeds and propagules banked in soil. Increased erosion during construction, in turn, buries underwater shoots and smothers seeds, tubers, resting buds, and shoot fragments in lake sediment (Kautsky 1987, Foote and Kadlec 1988). As water laps the base of shoreline structures, unrooted plants like coontail (*Ceratophyllum demersum* L.) and weakly rooted ones like American elodea (*Elodea canadensis* Michaux) drift away (Sculthorpe 1967), leaving sedges (*Carex*) and spikerushes (*Eleocharis*) that mat the lake bed with their roots and stolons (sediment-creeping stems).

Fragmenting lakeshore forests into buffer strips ultimately eliminates many songbirds. Vegetative buffers less than 250 ft wide in a Maine lake, for example, harbored fewer species and a lower density of songbirds (mostly warblers and sparrows) than did wider stretches of lakeshore forest, though several bird species nested only in the buffers (Johnson and Brown 1990). Even small buffers, however, can at first gain songbird species, as site-faithful migrants return to their cleared territories and then move into forested buffers (Rogers 1996).

Such fragmentation can isolate other migratory species. Shallow buffers not connected to uplands around a seasonally flooded South Carolina wetland ("Carolina bay") isolated turtles moving inland to nest (Burke and Gibbons 1995). This study highlights the importance of keeping at least patches and strips of varied lakeshore forest not only to provide vertical structure and nesting habitat but also to link land and water ecosystems.

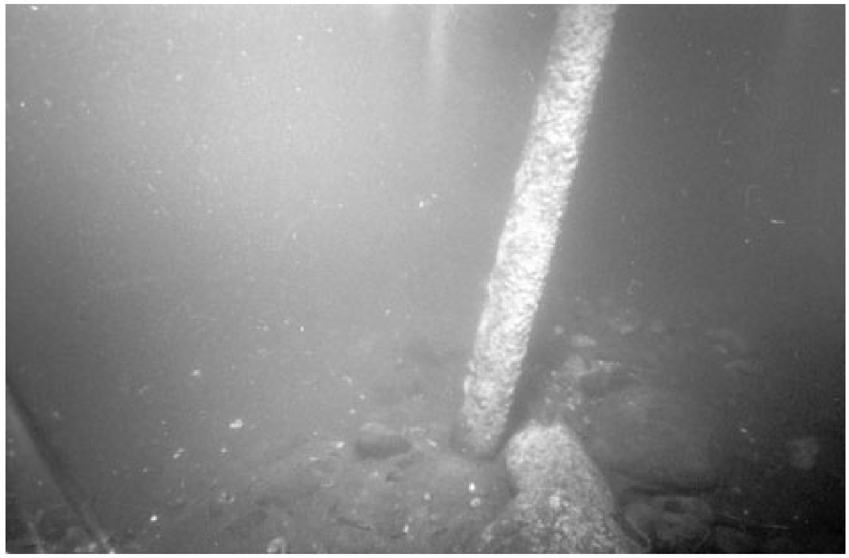
By destroying plant habitat, riprap and seawall construction could have widespread ecological effects. Yet most published studies we found were site specific—relating shoreline construction to plant loss and water turbidity at the site—and did not link shoreline construction to wider ecological change or rule-out confounding influences. For example, algal blooms that now shade-out underwater foliage could have resulted from nutrients washed off farms or city streets—nutrients now recycled from lake sediments (MacKenthun 1962, Bachmann and Jones 1974)

Creating lakeside lawns destroys annual and perennial ground cover for small animals. With ground cover gone, amphibians lose humid microclimates (Zug 1993), songbirds lose nesting materials (Austin 1961), and shore mammals lose burrowing habitat (Jackson 1961). Loss of ground cover confines these animals to fewer cover sites that predators need search. But removing ground cover along Ontario lakes had no affect on songbirds nesting beneath conifers, where ground cover is naturally sparse because of acidic soils, and even attracted disturbance-tolerant songbirds beneath deciduous trees (Clark et al. 1984).

Loss of underwater foliage opens invasion sites for exotic species. Shoot fragments of Eurasian watermilfoil (*Myriophyllum spicatum* L.) could take root and grow on disturbed sites, then spread by stolons and new shoot fragments (Engel 1993, 1995, 1997) to replace mixed beds of native plants. Turions of curly-leaf pondweed (*Potamogeton crispus* L.), itself a Eurasian import, can also sprout on disturbed sites (Sastroutomo et al. 1979). In Canada's Lake Opinicon, mixed beds of native pondweeds (*Potamogeton)* and wild celery (*Vallisneria americana* Michaux) supported 3–8 times as many macroscopic invertebrates as did pure (monotypic) beds of Eurasian watermilfoil (Keast 1984).

When plants are destroyed, invertebrates lose feeding sites and become exposed to fish predation. Crayfish (*Orconectes*) vulnerability to largemouth bass (*Micropterus salmoides* [Lacepède]) in an Arizona reservoir increased as the crayfishes grazed down their plant cover, became scarce, and then increased as the plant cover returned (Saiki and Tash 1979). With reduced plant cover the stirring, sorting, and transporting of shallow sediment by waves at the base of shoreline structures can wash away the silt and fine organic matter many insect larvae need for burrowing and case building (Hutchinson 1993).

Loss of submersed plants has different effects on juvenile and adult waterfowl. American black ducks (*Anas rubripes* Brewster), mallards, and wood ducks would lose plant-dwelling insect prey as ducklings but lose shoots, seeds, and tubers as adults (Stollberg 1950, Martin et al. 1961).



Absence of aquatic plant growth beneath a pier on Spread Eagle Chain, Florence County, Wisconsin.

Adding piers to lakeshores also destroys plant growth. Plants are uprooted during pier construction, and the piers continue to shade-out underwater foliage. But piers on wave-washed shores can form lee pockets that collect sediment for aquatic plants to take root. Water lilies (Nymphaeaceae) and even free-floating duckweeds (Lemnaceae), for example, can thrive behind wet boathouses and between closely spaced piers if boats are excluded. Using snow fencing or plastic sheeting to exclude motorboats from several 20 by 40-ft sites on hardwater Ripley Lake, in southern Wisconsin, increased the height and density of stoneworts (*Chara*) and spiny naiad (*Najas marina* L.), though plant growth appeared unrelated to water turbidity differences among the fenced sites (Asplund and Cook 1997).

Adding piers can increase boating pressure. Plants can be damaged directly from contact with boat hulls or motor propellers as well as indirectly from boat wakes formed at the bow and stern of passing boats (Liddle and Scorgie 1980). The plants disappear from boating lanes, become uprooted or shredded at the edge of the lanes, and grow slowly in water muddied by heavy boat traffic (Wagner 1990). Bottom scouring by boats can also damage plant buds, seeds, and tubers banked in bottom soil and expose the lake bed to invasions by exotic plant species able to cope with such disturbance.

Damage from boat wakes, however, depends on the speed and number of passing boats as well as boat shape (flat hulls versus keeled hulls), engine type (outboards versus inboards), and motor size (long versus short propeller shafts). Long flat-hulled boats with large outboard motors do more damage than short-keeled boats with small inboard motors (Liddle and Scorgie 1980). Incoming wakes scour the lake bottom to a water depth of about 3 ft, especially after plants have disappeared (Wagner 1990). Although boat wakes do less damage to cobbly shores than to mucky or peaty ones, the cobbles protect emersed plants on shore (Bonham 1983).

Aquatic plants differ in their resistance to flow (Haslam 1978) and thus to damage from boat wakes. Floating-leaf plants are more damaged than submersed or emersed ones, because boat wakes are strongest at the water surface and diminish with depth. Many emersed plants not only grow on shore but also form stout roots and lignin-reinforced shoots that resist boat wakes. Well-rooted submersed plants, such as Eurasian watermilfoil, are less apt to be dislodged by passing motorboats than unrooted or weakly rooted ones, such as coontail and American elodea. Plants with pliable stems and short growth, such as pipewort (*Eriocaulon*) and waterwort (*Elatine*), are less damaged by boats than those with brittle stems and tall growth, such as spiny naiad and curly-leaf pondweed. Plants able to arch their shoots over the bottom and dispense with floating leaves, such as fern-leaf pondweed (*Potamogeton robbinsii* Oakes), can also thrive beneath boat traffic.

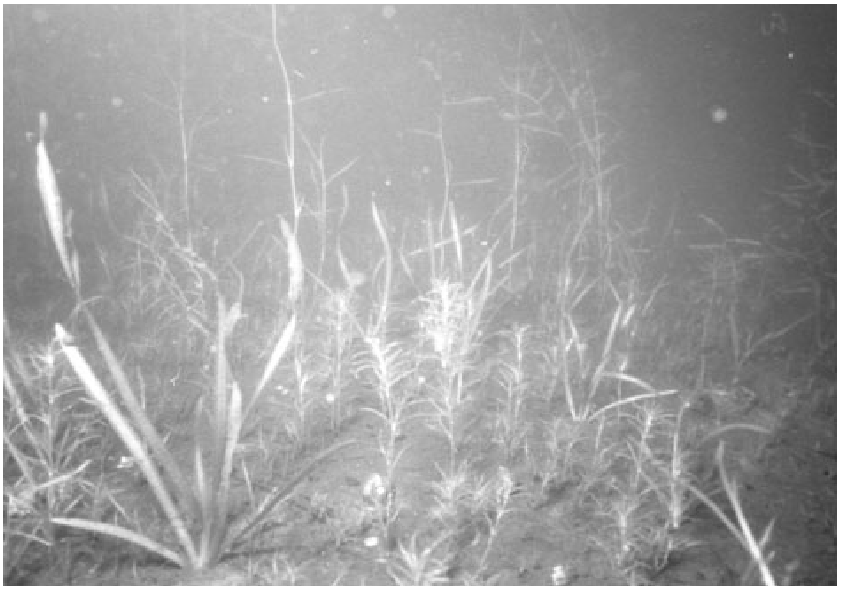


PHOTO: TIMOTHY F. RASMAN (DNR)

Submersed rooted plants growing away from the shade of piers in Spread Eagle Chain, Florence County, Wisconsin.

Even the same species can differ in susceptibility to boat damage. Although the brittle leaves of curly-leaf pondweed are easily torn, their flexible shoots resist the shearing action of turbulent flow (Haslam 1978). Water lilies have strong upright petioles (leaf stalks) and flat leaf blades (lily pads) that also resist water turbulence, yet the plants are easily uprooted (Sculthorpe 1967). Survival can depend on which characters are affected most by the passing boats.

Plants also differ in their vulnerability to bottom fabrics (Eichler et al. 1995). Shade-tolerant submersed plants, such as American elodea and Eurasian watermilfoil, can grow beneath fiberglass screens not firmly anchored (Pullman 1981, 1990) or take root in sediment that collects on blankets and liners (Lewis et al. 1983, Engel and Nichols 1984). Exotic plants can also take root when synthetic fabrics, exposed to sunlight at the water's edge, become brittle and crack (Engel 1984).

Macroscopic Invertebrates

The density of macroscopic invertebrates (macroinvertebrates) depends on the area colonized and decreases as the substrate becomes simpler and less stable (Hutchinson 1993, Death 1995). Invertebrates gain 30–50 times more surface area in colonizing macroscopic plants than a flat lake bed (Edwards and Owens 1965). In the absence of fish predation (Gilinsky 1984), invertebrate abundance varies by plant type. Macroscopic invertebrates are more abundant on submersed plants than emersed ones (Voigts 1976), more abundant in mixed beds than in monotypic ones (Keast 1984), and more abundant on plants with compound leaves than with simple ones (Krecker 1939, Mrachek 1966). Even finely leaved plastic plants harbor more aquatic insects and snails than do plastic plants or real ones with broad leaves (Krull 1969, Gerrish and Bristow 1979).

Lakeside construction can smother invertebrate communities when soil sloughs onto the base of shoreline structures (Krull 1969). Sloughing can be extensive after heavy rains, especially on steep shores formed of sandy loam with little clay (Bhowmik 1978). Stripping away vegetation before construction and not stabilizing slopes with filter fabric, hay bales, or silt fences increase the likelihood that soil-dwelling invertebrates will also be lost during construction.

Sloughed or eroded sediment coats wave-washed sand, gravel, cobbles, and boulders near shore. The sediment not only abrades snail and clam shells but also hinders invertebrate filter feeding, underwater air breathing, and egg development (Hutchinson 1993). It further dampens water movement and the exchange of dissolved oxygen and carbon dioxide at the boundary layer between water and substrate, where many stone-dwelling (epilithic) invertebrates live.

But riprap, unlike new seawalls, provides invertebrates with concealment sites in the crevices between stones and with feeding sites when the stones become coated with algae and detritus. Different species of algae coat rocks above and below the water level, depending on slope, wave action, water chemistry, exposure to air and spray, and the size and shape of the rocks (Hutchinson 1975). The density of macroscopic invertebrates, especially midge larvae, during summer in a Tennessee Valley Authority reservoir significantly decreased from riprap to natural shores to seawalls, partly because crevices in the riprap increased the surface area for invertebrate colonization (Hylton and Spencer 1986).

Crevices in riprap also attract collectors and gatherers—invertebrates able to browse algae and detritus. Collectors and gatherers, for example, dominated macroscopic invertebrate communities on a stony, windswept New Zealand lakeshore (Death 1995). While sediment attracts collectors and gatherers, it clogs the feeding apparatus of filter feeders like clams and bryozoans (Tockner 1991).

With the expanded microhabitat and surface area of crevices, riprap can attract a variety of other invertebrates. Rotifers (Rotifera: Monogononta), true worms (Oligochaeta: Naididae), water fleas (Cladocera: Chydoridae), freshwater scuds (Amphipoda: Gammaridae), snails (Gastropoda: Physidae), and midge larvae (Diptera: Chironominae) use crevices to tear, scrape, and gather algae and detritus (Cummins 1973, Cummins and Merritt 1984, Hutchinson 1993). These invertebrates, in turn, attract predators such as water bugs (Hemiptera: Belostomatidae), diving beetles (Coleoptera: Dytiscidae), and damselfly nymphs (Odonata: Coenagrionidae). Together, this riprap fauna draws minnows and largemouth bass (Prince and Maughan 1979).

PHOTO: FORREST E. BEALS

A fiberglass screen, weighted with rebar, being set by divers on the bottom of Pipe Lake, King County, Washington.

Cracked and crumbling seawalls, though less effective at erosion control than well kept ones, could increase invertebrate density and diversity by also providing crevices for feeding and egg laying (Williams and Feltmate 1992). But we found no published studies comparing the invertebrate densities of new and old seawalls.

Both riprap and seawalls, with solid attachment for snails and clams, can also attract exotic species (Lodge 1993) like zebra mussels (*Dreissena polymorpha* [Pallas]). In the Laurentian Great Lakes, these clams encrust cobble stones (Bailey et al. 1995), water intakes, and boat hulls (Griffiths et al. 1991, Mellina and Rasmussen 1994)—solid substrates not unlike bouldery riprap and vertical seawalls in smaller lakes.

Because rock substrates, such as riprap and crumbly seawalls, are difficult to sample and vary in surface configuration, artificial substrate samplers have been used to provide a standard surface to compare substrate preference of macroscopic invertebrates. These devices include Hester-Dendy samplers with stacked wooden plates, cloth or wire baskets with gravel or cobbles, and various arrangements of synthetic construction webbing (Mason et al. 1973). Compared to bottom Ponar grabs, for example, rockfilled wire baskets in California's Sacramento River at Freeport Bridge attracted a greater number and diversity of macroscopic invertebrates, including snails, sow bugs (Crustacea: Isopoda), and midge larvae (Slack et al. 1986). No effort was made, however, to determine whether these invertebrates were drawn to wire baskets without rocks: Habitat assessment was not separated from sampling method.

Piers and bottom fabrics decrease habitat for invertebrates by shading-out underlying plants. Bottom fabrics further deplete dissolved oxygen beneath them (Engel 1984)—suffocating underlying invertebrates—and prevent larval emergence from underlying burrows (Engel 1984, Bartodziej 1994). Although some invertebrates, such as midge and caddisfly larvae, colonize the underwater surfaces of pier supports and bottom fabrics, they lose more substrate when plants and dissolved oxygen disappear.

Removing woody debris from lake beds takes out invertebrates on the debris and reduces invertebrates beneath it. Because of larger surface area, brush takes out more invertebrates than would logs (Harmon et al. 1986). This leaves fewer invertebrates to colonize the underlying soil and less debris to enrich the soil with organic remains that invertebrates use to burrow and build cases.

PHOTO: FORREST E. BEALS

A private beach kept free of surrounding water lilies by fiberglass screen in Pipe Lake, King County, Washington.

Nearshore Fishes

Fish Habitat. Lakeshore development can affect many Wisconsin fish species, because most of them spend at least part of their life cycle near shore (Becker 1983, Fago 1992). Some nearshore fish assemblages may constitute habitat or trophic guilds whose members respond alike to environmental change (Austen et al. 1994).

Habitat preferences, however, differ among fish species. Inshore fish sampling in Lake St. Clair found 11 species along wetlands, 10 species along undeveloped shores, 6 species along developed shores, and 5 species along beaches (Brazner and Magnuson 1994). Bluegills (*Lepomis macrochirus* Rafinesque) and black bass in this lake preferred altered (dredged and bulkheaded) shores, whereas minnows and darters (*Etheostoma* and *Percina*) preferred unaltered shores (Poe et al. 1986). In lakes with sparse rooted vegetation, more nearshore fishes use rocky and bouldery shores than use sandy and gravelly ones (Emery 1978, Beauchamp et al. 1994). Only occasionally do sandy and rocky shores attract more fishes, if fewer species, than bouldery or well-vegetated shores (Guillory et al. 1979).

Plant habitat attracts fishes in variety and abundance. Plant beds harbored 11 fish species—beach habitat, only 7 species—in central Florida's Lake Conway (Guillory et al. 1979). Plant cover was positively correlated ($P < 0.05$) with fish abundance in Florida's Lake Okeechobee (Chick and McIvor 1994), Iowa's Spirit Lake (Bryan and Scarnecchia 1992), and 25 central Ontario lakes (Hinch and Collins 1993). Plant species diversity was positively correlated ($P < 0.05$) with fish species diversity among 6 Wisconsin lakes, especially when depth was considered (Benson and Magnuson 1992). Plant beds enable bluegills and pumpkinseed sunfish to coexist despite predation pressure from largemouth bass (Mittelbach and Chesson 1987).

Many small fishes seek plant beds as refuge from predators but will use piers, boulder spits, rock outcrops, and woody debris especially when plant beds are scarce. Young fishes, including those of black bass and northern pike (*Esox lucius* L.), hide among thick foliage when piscivores (fish eaters) are present but stay outside thick foliage or seek sparse foliage when such predators are absent (Johnson et al. 1988, Lynch and Johnson 1989). Stocked fingerling muskellunge use emersed, floating-leaf, and submersed foliage as nursery areas for hiding and feeding (Hanson and Margenau 1992). Log perch (*Percina caprodes* [Rafinesque]) and mottled sculpins (*Cottus bairdi* Girard) seek crevices between rocks and boulders in lakes with sparse vegetation. Rock bass (*Ambloplites rupestris* [Rafinesque]) seek underwater brush piles by day but leave them by night (Rodeheffer 1940).

Some large fishes are also attracted to plant beds. Adult muskellunge (*Esox masquinongy* Mitchill) and northern pike with ultrasonic transmitters have been tracked to plant beds, especially pondweeds on sunny days (Crossman 1977, Diana et al. 1977). Largemouth bass switch hunting tactics from cruising to ambushing prey as plant density increases (Savino and Stein 1989). Even walleyes (*Stizostedion vitreum* [Mitchill]) cruise plant beds for such prey fish as yellow perch (Engel 1997).

Fishes also seek boulder spits, rock outcrops, and woody debris for prey, though fish species differ in what prey they capture. Specialized feeders like black crappies (*Pomoxis nigromaculatus* [Lesueur]) select a few small prey, such as midwater zooplankton, whereas more generalized feeders (opportunists) like bluegills select a broad array of larger prey, such as bottom-or plant-dwelling midge and caddisfly larvae (Keast 1970). Plant-dwelling rock bass and pumpkinseed sunfish (both 2.2–3.7 inches in total length) in Lake St. Clair ate insects on or beneath plant shoots, though rock bass took fewer but larger ones than did pumpkinseed sunfish (French 1988).

Some fishes can shift diet and habitat as food competition and prey availability change (Mittelbach 1983). For example, bluegills shift to eating smaller prey as large ones dwindle during summer (Mittelbach 1981) and shift from plant-dwelling prey to open-water ones when bottom-feeding pumpkinseed sunfish are present (Werner and Hall 1977). They also shift to open-water or bottom-dwelling prey when the plant beds or woody debris they inhabit are decimated (Bettoli et al. 1993), though small bluegills then face increased predation.


PHOTO: TIMOTHY F. RASMAN (DNR)

Leaf litter and a submerged brush pile with the gelatinous egg mass of a yellow perch in Spread Eagle Chain, Florence County, Wisconsin.

The value of plant beds to fishes differs with plant density. Dense plant beds in aquaria (46 stems/ft^2), for example, afford age-0 bluegills (1.7–2.5 inches in total length) maximum protection against fish predators but hinder bluegill feeding on insects (Gotceitas 1990*a*). Plant beds of modest density (10 stems/ft^2) afford plant-dwelling bluegills a better compromise between food and safety (Wiley et al. 1984). However, age-0 bluegills (>2.0 inches in total length) kept for 117 days in lake enclosures differing in artificial plant density (0, 37, 89, and 324 stems/ft^2) showed no significant ($P > 0.05$) difference in growth (Hayse and Wissing 1996), because the bluegills could eat zooplankton outside the plants and dart for cover when threatened.

Fish use of woody debris varies with the type and arrangement of debris and the age and species of fishes (Wege and Anderson 1979, Moring et al. 1986). Bluegills prefer woody debris built of evergreen trees to brush piles, especially when the trees are compacted (Johnson and Lynch 1992). Tree tops sunk with cinder blocks attract bluegills and largemouth bass mostly shorter than 5.9 inches in total length (Graham 1992). Adult largemouth bass also visit woody debris as well as piers but seldom linger (Prince and Maughan 1979, Colle et al. 1989). Male smallmouth bass (*Micropterus dolomieu* Lacepède) in Wisconsin lakes, however, excavated nests near logs and boulders for their own cover and that of newly hatched fry (Baylis et al. 1993). Largemouth bass in an Arkansas reservoir preferred to nest in coves with artificial brush piles, though smallmouth bass showed no such preference (Vogele and Rainwater 1975).

Habitat Loss. By destroying plant beds, lakeshore development restricts opportunities for resource partitioning through food specialization. For example, in 5,600-acre Spirit Lake, Iowa, juveniles of 18 fish species were scarcer along shores developed with piers, homes, and beaches than along shores with emersed and submersed plant beds, though juveniles in water deeper than 6.6 ft had similar abundance between developed and undeveloped shores; smallmouth bass at all depths were found in equal or greater abundance along developed shores (Bryan and Scarnecchia 1992). Fish species differ in when they become vulnerable to predators after plant loss (Briggs and O'Connor 1971). Many minnows seek natural cover after hatching (Hubbs and Cooper 1936, Becker 1983), whereas bluegills in the Midwest seek open water after hatching in June and move inshore when about an inch long in late August (Werner 1969).

Lakeside construction can also increase siltation and water turbidity that, in turn, can reduce feeding and spawning of many lake fishes (Becker 1983), including pugnose shiners (*Notropis anogenus* Forbes) threatened in Wisconsin. Adding bentonite clay to plastic wading pools with bluegills that

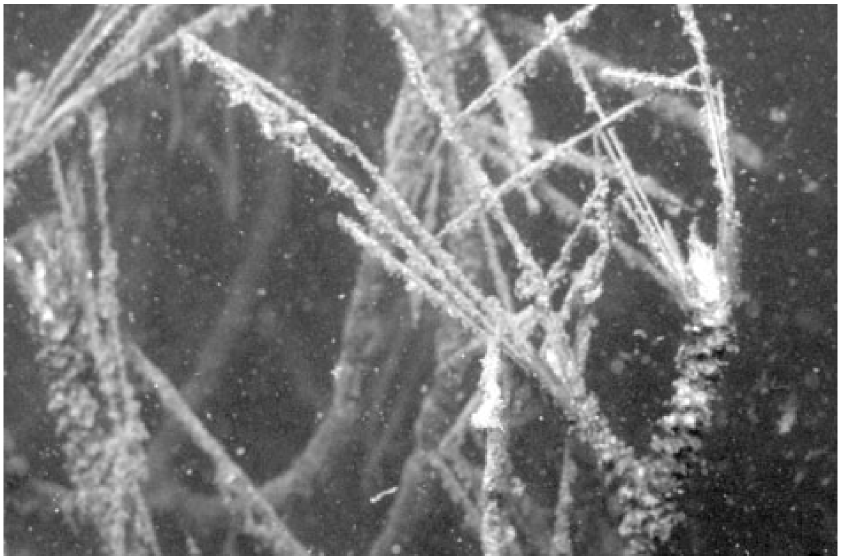


PHOTO: TIMOTHY F. RASMAN (DNR)

Fish-eye view of a brush pile showing detritus-coated branches in Spread Eagle Chain, Florence County, Wisconsin.

average 3.0 inches in total length reduced feeding rates on daphnia (*Daphnia pulex* Leydig), though prey size selectivity was unchanged (Gardner 1981). Similar aquarium tests on striped bass (*Morone saxatilis* [Walbaum]) that range from 0.4 to 0.9 inches in total length also reduced feeding rates on copepods (chiefly *Eurytemora affinis* [Poppe]), though not on *D. pulex* (Breitburg 1988). Silt from construction sites can smother fish nests and scattered eggs (Karr and Schlosser 1978), impairing embryonic development and keeping yolk-sac fry from becoming free swimming (Mitzner 1987). However, riprap and seawalls are meant to control erosion and thus should ultimately improve water clarity.

Woody debris removal decreases habitat structural complexity, especially on windswept shores naturally devoid of plant beds (Crowder and Cooper 1982). Such shores offer bluegills, black crappies, and pumpkinseed sunfish few microhabitats and less opportunity for resource partitioning (Werner et al. 1977). Logperch (*Percina caprodes* [Rafinesque]) and mottled sculpins, however, prefer open shores for bottom feeding especially at night (Becker 1983). Pumpkinseed sunfish even prefer to nest in areas of a Canadian lake that were cleared of all woody debris longer than 10 inches (Colgan and Ealey 1973). Although bluegills gain shelter from plant cover and woody debris, feeding is more profitable on zooplankton in open water (Werner et al. 1983).

The cumulative effects of woody debris removal ultimately are complex. Some fish species, particularly when young, prefer to nest near such structures for shelter and invertebrate prey. Other fish species prefer to nest along open shores to gain increased space for feeding on zooplankton or bottom-dwelling prey at night. Bluntnose minnows (*Pimephalis notatus* [Rafinesque]) and mudpuppies (*Necturus maculosus* [Rafinesque]) attach their eggs to the undersides of submerged rocks or logs (Hubbs and Cooper 1936, Wright and Wright 1949) and, therefore, could lose egg-laying sites when woody debris is removed.

Small cumulative effects of lakeshore development on warmwater fishes can go unnoticed yet have important consequences. Consider a small reduction in feeding caused by loss of prey habitat. Bioenergetic modeling of largemouth bass held at 81.5°F predicts that a 20% decrease in feeding rate would reduce net growth from spring to fall by 64% (Rice 1990). Such stress affects young fishes more than older ones (Shuter 1990). Slower growth of young-of-year black bass means less fat deposition and thus reduced first winter survival (Miranda and Hubbard 1994). Natural variations in year-class strength, however, can mask growth responses to habitat disturbance.

Fish Use of Dockage. Piers, boat shelters, and canopied lifts are used by nearshore fishes for shade and shelter but rarely for feeding and nesting, because these structures lack the structural complexity of plant beds, rocky substrates, and woody debris. For example, piers were preferred habitat for 4 of 27 radio-tagged largemouth bass in a Florida lake after stocked grass carp (*Ctenopharyngodon idella* [Valenciennes]) had decimated most plant beds, but the bass seldom lingered under the piers and sought the remaining fringe of plant beds (Colle et al. 1989).

Opaque structures over water cast shade during daylight to conceal objects beneath them and highlight objects outside the structures. Hovering beneath floating objects, prey fishes are hidden from outside view and can see predators up to 2.7 times the visual distance that predators can see the prey (Helfman 1981); predators are also disadvantaged by the glare of downwelling scattered light hitting their eyes (Helfman 1977). Floating boards stationed in a New York lake, for example, attracted many more bluegills and pumpkinseed sunfish that were 3.1–4.7 inches in total length than did floating rings without shade-casting boards (Helfman 1979). Fish densities under the boards varied from 1.1 to 7.7 fishes/ft^2 and were highest around noon on sunny days, moderate on overcast days, and lowest at night. Black crappies and golden shiners (*Notemigonus crysoleucas* [Mitchill]) were also attracted to the floating boards but hovered just outside them. Bluegills and pumpkinseed sunfish more than 4.7 inches in total length and all rock bass, largemouth bass, yellow perch, and white suckers (*Catostomus commersoni* [Lacepède]) showed no positive or negative attraction to the boards.


PHOTO: TIMOTHY F. RASMAN (DNR)

Trees leaning along a steep slope could become deadfalls that form coarse woody debris in Bass Lake, Oconto County, Wisconsin.

Shade-casting objects like piers, however, do not always attract fishes in full sunlight and can shade-out plants that conceal fishes from predators. Piers, boat shelters, and canopied lifts cast maximum shade when close to the water surface. The shade advantage of such objects is lessened when lake water is turbid or at low level. Nearshore fishes in Lake Tahoe, for example, showed no significant preference for hovering under any of 70 piers examined, regardless of bottom composition, perhaps because low water level from prolonged drought kept most piers from casting sufficient shade to conceal the fishes (Beauchamp et al. 1994). Plant beds, rock outcrops, boulder spits, and woody debris can draw fishes away from piers, despite adequate shade.

Amphibians and Reptiles

The home ranges of many amphibians and reptiles include lakeshores for access (corridors) between water and land as well as habitat to bask, feed, nest, and overwinter (Goin et al. 1978, Zug 1993). For example, adult American toads (*Bufo americanus* Holbrook), gray treefrogs (*Hyla versicolor* LeConte), and northern spring peepers (*Pseudacris c. crucifer* [Wied-Neuwied]) leave woodlots in early spring to breed in lake shallows; snapping turtles (*Chelydra serpentina* [L.]) leave water in late spring or summer to nest inland (Vogt 1981). Adult green frogs (*Rana clamitans* Latreille), in contrast, stay near the water's edge where males establish summer territories (Oldfield and Moriarty 1994). Northern water snakes (*Nerodia sipedon* [L.]) and painted turtles (*Chrysemys picta* Schneider) both feed in water but need to bask on deadfalls or floating logs for drying the skin or shell, absorbing calcium from food, and raising body temperature (Boyer 1965). Such shore-dependent species, consequently, are sensitive to direct human disturbance and indirect habitat change at the water's edge.

Development can fragment lakeshore vegetation into "island" habitats that force frogs and turtles to spend extra time and energy seeking access to nesting sites. Bullfrogs (*Rana catesbiana* Shaw) and green frogs breed on floating-leaf plants near the water's edge (Wright and Wright 1949, Howard 1978), plants that could disappear with successive lakeshore development. Extensive development could leave so little intervening cover that local populations become isolated and even extirpated (Brode and Bury 1984, Quinn and Karr 1993).

Sparse ground cover in summer increases ground temperatures, evapotranspiration rates, and the potential for desiccation of amphibians. Exposed pond margins, for example, attracted radio-tagged northern leopard frogs (*Rana pipiens* Schreber) in spring but proved too dry for the frogs in summer (Hine et al. 1981).

Removing brush, deadfalls, and decaying logs along shore robs salamanders of moist cover for feeding and robs turtles of dry perches for basking (Zug 1993). Forcing turtles to bask atop riprap or seawalls could expose the turtles to predators.

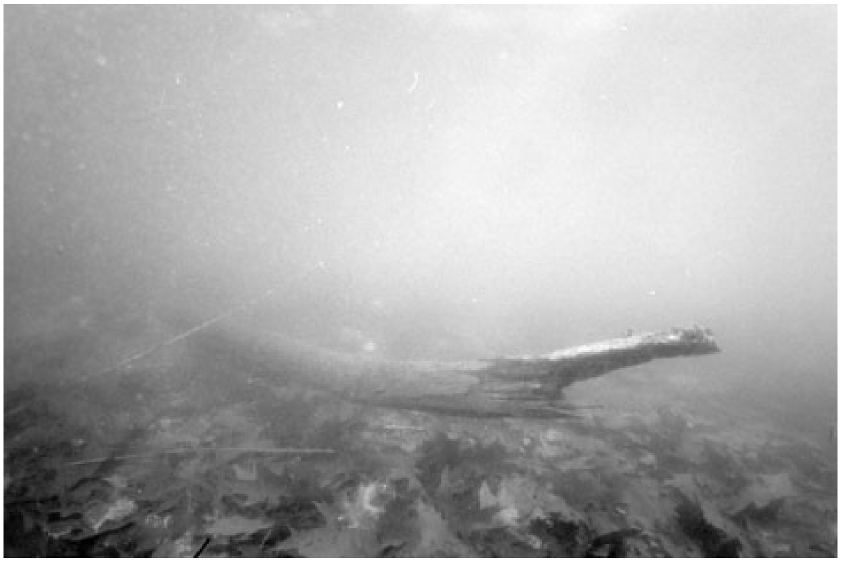


PHOTO: TIMOTHY F. RASMAN (DNR)

Leaf litter and a sunken log that could attract nesting black bass in Spread Eagle Chain, Florence County, Wisconsin.

Bald eagles (*Haliaeetus leucocephalus* [L.]), for example, grab sunning turtles off logs and boulders to supplement a predominantly fish diet for themselves and their nestlings (Clark 1982). Foxes and other mammals hunt turtles on shore. But we found no study comparing predation on basking amphibians or reptiles along developed versus undeveloped shores.

The effects of habitat loss on amphibians and reptiles differ by age as well as species, especially when home ranges change with maturity. Bullfrogs, a Wisconsin watch species sensitive to plant habitat disturbance, live on shore as adults but are strictly aquatic as tadpoles (Martof 1953, Brown 1972, Cecil and Just 1979). Both adults and tadpoles need dense plant cover to escape predators (Raney 1940, Wright and Wright 1949, Wiewandt 1969) and thus would disappear from cleared shores.

But small lakeshore alterations may not harm some widespread species that are niche generalists. Northern leopard frogs during summer, for example, occupy a variety of habitats, including construction sites up to a mile from standing water (Vogt 1981). American toads and snapping turtles can cross hills and roads during breeding migrations, though seawalls could block their exit from water. Painted turtles, whose populations can be limited by competition for scarce basking sites (Ross 1989), could bask on riprap but favor offshore logs and mats of floating-leaf plants for quick escape from land predators. Riprap and seawalls can provide basking sites for (nonvenomous) northern water snakes (*Nerodia sipedon* L.) and common garter snakes (*Thamnophis sirtalis* [L.]), though riprap provides easier access from water to land and more crevices for feeding and hibernating than do seawalls.

Birds and Mammals

A variety of shorebirds, songbirds, waterfowl, and mammals can be just as shore dependent as amphibians and reptiles. Because these birds and mammals need plant habitat for food, cover, nesting, and perching (Moyle and Hotchkiss 1945), they too are vulnerable to habitat loss from lakeshore development. Their sensitivity to shoreland disturbance likewise varies with age and species.

Natural shorelines offer diverse nesting habitat. Common loons (*Gavia immer* [Brünnich]) use available plant matter to build nests near the water's edge (Klein 1985, McIntyre 1988), where they can be disturbed by shoreline construction, speed boaters, and even canoers (Titus and VanDruff 1981). Wood ducks (*Aix sponsa* [L.]) nest in tree holes near water but can brood in dense cover up to 100 ft from shore (Bellrose and Holm 1994). Ducklings and bank rodents are vulnerable to raptors when cover is sparse, as would be expected along developed shores. But raptors themselves need tall trees to nest and thus disappear when the trees are cut. Beavers (*Castor canadensis* Kuhl) and muskrats (*Ondatra zibethicus* [L.]) use cattails (*Typha*), bulrushes (*Scirpus*), and tree branches to build lodges, where a variety of aquatic plants are cached as winter food (Bellrose 1950, Sather 1958, Errington 1963).

Natural shorelines also support food plants and associated prey. Swans (*Cygnus*) and geese (*Anser* and *Branta*), for example, eat young roots, shoots, and rhizomes especially of emersed plants (Austin 1961). Dabbling ducks (*Anas* and *Aix*) and American coots (*Fulica americana* Gmelin) eat seeds, tubers, and macroscopic invertebrates from emersed and floating-leaf plants (Martin and Uhler 1939). Diving ducks (*Aythya*) pick tubers and macroscopic invertebrates off submersed plants or the lake bottom (Bellrose 1980). Meadow voles (*Microtus pennsylvanicus* [Ord]), minks (*Mustela vison* Schreber), river otters (*Lontra canadensis*

[Schreber]), and starnose moles (*Condylura cristata* [L.]) eat emersed plants and burrow into banks (Burt 1957, Jackson 1961). White-tailed deer (*Odocoileus virginianus* [Zimmermann]) sometimes browse shoreline conifers and shrubs in winter (Dahlberg and Guettinger 1956, Beier and McCullough 1990) and pondweeds in summer (Townsend and Smith 1933).

Loss or fragmentation of plant cover along shore not only robs birds of food and shelter but also squeezes them onto a few small sites, increasing their risk from storms (Swanson and Duebbert 1989). Storms force dabbling ducks, especially during brood care, to seek protective coves and overhanging vegetation (Schroeder and Allen 1992). Although trees may still stand along developed shores, loss of contiguous canopy and understory growth destroys the vertical stratification of foliage that migratory and breeding songbirds, such as wood warblers (Parulinae), need for habitat segregation (Clark et al. 1983).

PHOTO: SANDY ENGEL

Lakeshore habitat crowded with water lilies (foreground), pickerelweed (Pontederia cordata L.), and cattails (background) on Round Lake, Rusk County, Wisconsin.

Adding lakeshore homes increases predation pressure on ground nesting birds and mammals. The homes attract raccoons (*Procyon lotor* [L.]) and striped skunks (*Mephitis mephitis* [Schreber]) to bird feeders and garbage cans (Jackson 1961), where these scavengers can attack shorebirds and mammals. Herring gulls (*Larus argentatus* Pontoppidan) also congregate at times along developed shores, where they steal eggs from unguarded nests of common loons (McIntyre 1988).

Domestic cats (*Felix catus* L.) also scavenge near homes and become free-ranging predators when released by pet owners at night (Coleman and Temple 1993). Radio-tag studies reveal male and female cats establish home ranges (Liberg 1980) and hunt along fence rows, field and forest edges, and roadsides when prey is plentiful (Warner 1985, Churcher and Lawton 1987). Even well-fed cats hunt rabbits, rodents, and songbirds and can outcompete native mammalian predators when prey is scarce (Coleman and Temple 1993). Declawed cats can stalk birds at feeders and chicks on ground nests, though island-nesting birds are safe from most cats and other mammalian predators (McIntyre 1988). Boathouses may shelter free-ranging cats, much as abandoned buildings do in cities (Calhoon and Haspel 1989). But we found no published studies of cat abundance or predation along lakeshores.

Removing lakeshore vegetation also robs mammals of food, shelter, and thermal cover. By reducing conifer browse, cottage development along Ontario lakes reduced the winter density ("carrying capacity") of white-tailed deer from 31 to 5 deer/mile^2 (Armstrong et al. 1983, Voigt and Broadfoot 1995). But loss of conifer fringe in northern Wisconsin may affect winter deer travel more than survival, given the growing popularity of recreational deer feeding and the availability of deer yards (Dahlberg and Guettinger 1956).

Removing tall trees along shore robs raptors of trees to build nests and spot prey, though studies are scarce on lakeshore use by owls (Strigiformes) and hawks (*Buteo*). Bald eagles along the Chesapeake Bay were more common on undeveloped shores with trees at least 20-ft tall within 30 ft of water (Chandler et al. 1995). Their shoreline use along the bay was inversely related to building density (Buehler et al. 1991), partly because of disturbance from motorboating. Bald eagles here and along lakes in Maine (Livingston et al. 1990) and Minnesota (Fraser et al. 1985) did nest on developed shores but spent more time and energy feeding, because their nests were significantly ($P < 0.05$) farther from water than were nests on

PHOTO: SANDY ENGEL

Water lilies (foreground) and cattails (background) growing near riprap and a pier on Hilbert Lake, Marinette County, Wisconsin.

undeveloped shores. Leaving trees along developed shores can screen raptors from pedestrians (Chandler et al. 1995), though bald eagles avoid nesting in even-aged stands with unbroken canopy (Stalmaster 1987).

Some waterbirds tolerate lakeshore development better than others. Herring gulls can nest on riprapped islands for protection from mammals (Mossman et al. 1988). Diving ducks, such as canvasbacks (*Aythya valisineria* [Wilson]) and redheads (*A. americana* [Gmelin]), feed on snails and plant tubers in deep water (McAtee 1939, Jahn and Hunt 1964, Kahl 1991*a*), though these birds still cannot escape motorboats. But common loons, with legs positioned far to the rear, are clumsy on land (McIntyre 1988) and could be hindered by seawalls to climb. Dabbling ducks, such as mallards and blue-winged teals (*Anas discors* L.), use woody debris for feeding and perching.

Piers have direct and indirect effects on waterbirds. Waterfowl use piers as loafing and preening sites, the extra height above the water improving their detection of predators. But this advantage cannot replace the loss of feeding, nesting, and concealment habitat and the human disturbance that piers cause. Installing piers where waterfowl breed limits egg laying and forces nesting pairs to choose less favorable sites (Dahlgren and Korschgen 1992). Adding piers can increase boating pressure, forcing waterbirds like migratory diving ducks to spend less time feeding and more energy flying between resting sites (Korschgen et al. 1985, Kahl 1991*b*).

Human disturbances along developed shores can limit shoreline nesters. Common loons have their best success nesting along undisturbed lakeshores, especially islands (Vermeer 1973, McIntyre 1988), and are significantly ($P < 0.05$) more common on Wisconsin lakes with fewer than 1 dwelling per 10 acres of lake surface (Zimmer 1979). Boat wakes can washout common loon nests, especially when water levels are high (Vermeer 1973). Boaters and pedestrians can scare loon parents off nests, exposing the eggs to predators (Strong et al. 1987), or separate chicks from parents, causing the chicks to starve or fall victim to predators (Barr 1996). But some loons learn to stay on nests or move chicks to quiet areas when disturbed (Heimberger et al. 1983). They can also renest, though time for brood care is then shortened (McIntyre 1988). But the demise of breeding loons a century ago from many lakes on their southern fringe (Bent 1919), including those in southern Wisconsin (Zimmer 1979), resulted from sport hunting more than boating pressure or lakeshore development (McIntyre 1988).

Mitigation and Management of Lakeshore Development

Lakeshore Planning

Shoreline mitigation and management starts with planning. Design and construction errors, aesthetic problems, and ecological effects after construction can be minimized with a plan to define problems, set goals, and guide development (Macbeth 1992). Planning can help identify critical lakeshore habitats as *sensitive areas* (s. NR 107.05, Wis. Adm. Code), avoid development clusters on popular shores, and shift development pressures to back lots. It can also help identify development alternatives and improvements to existing structures so they blend with surroundings. Planning can also help divide responsibilities, coordinate management efforts, and encourage citizen support (Engel 1989). As demand for water and shore space increases (Threinen 1964) so, too, does the need for planning.

Consider erosion control. Planning forces lakefront property owners to assess the nature and extent of problems at the shore before deciding if erosion control is needed and what corrective actions to take. Some erosion problems are more apparent than real or require only minor correction. Small problems can be solved by the owner; large ones will need an experienced engineer, lake manager, or both.

Planners should gather information on management options, such as controlling erosion with riprap, gabions, brush bundles, lakeshore plantings, or a combination of methods. Improper shore protection not only wastes time, labor, and money but also increases habitat loss and shore erosion. Adjacent property owners should be contacted before construction to avoid overdevelopment and coordinate shoreline protective measures. Before construction, owners must apply for a permit under chapter 30 of the Wisconsin Statutes and should follow local and county ordinances, though federal permits are usually not necessary on most inland lakes in Wisconsin.

Lakeshore plans can be no more than lists of objectives and a lake map showing present shoreline structures, plant and woody debris habitats, and proposed new developments (Engel 1989). Or they can be comprehensive documents developed after lake surveys have revealed causes, consequences, and correctives. These surveys might lead to *habitat protection plans* for setting aside sensitive areas or *habitat restoration plans* for replanting habitat long ago lost. These habitat plans can be integrated with watershed management plans to reduce nutrient runoff or with fish management plans to improve angling.

Such comprehensive planning can integrate specialty plans that focus on land use, lake use, and *aquascaping* (underwater landscaping). *Land use plans* can help protect floodplains against home and road construction (Burbridge 1994) that destroy vegetative buffers for amphibians, reptiles, and mammals. The plans can also establish guidelines for lot widths and home setbacks to avoid lakeshore crowding. *Lake use plans* can help set aside vegetative buffers for wildlife and create space or time zones (Figure 3) for angling, canoeing, swimming, sailboating, and motorboating (Engel 1989). Use of canoes and personal watercraft, for example, might be restricted to different parts of a lake or hours of the day. *Aquascaping plans* can help improve lakeshore habitat by showing where native trees, shrubs, and aquatic herbs (macrophytes) can be planted to screen shoreline structures or improve existing vegetative buffers (Miller 1988, Pullman 1989).

Lake Classification

Lakes differ in their potential for recreation, habitat protection, and lakeshore development. Some lakes are good for motorboating; others are best

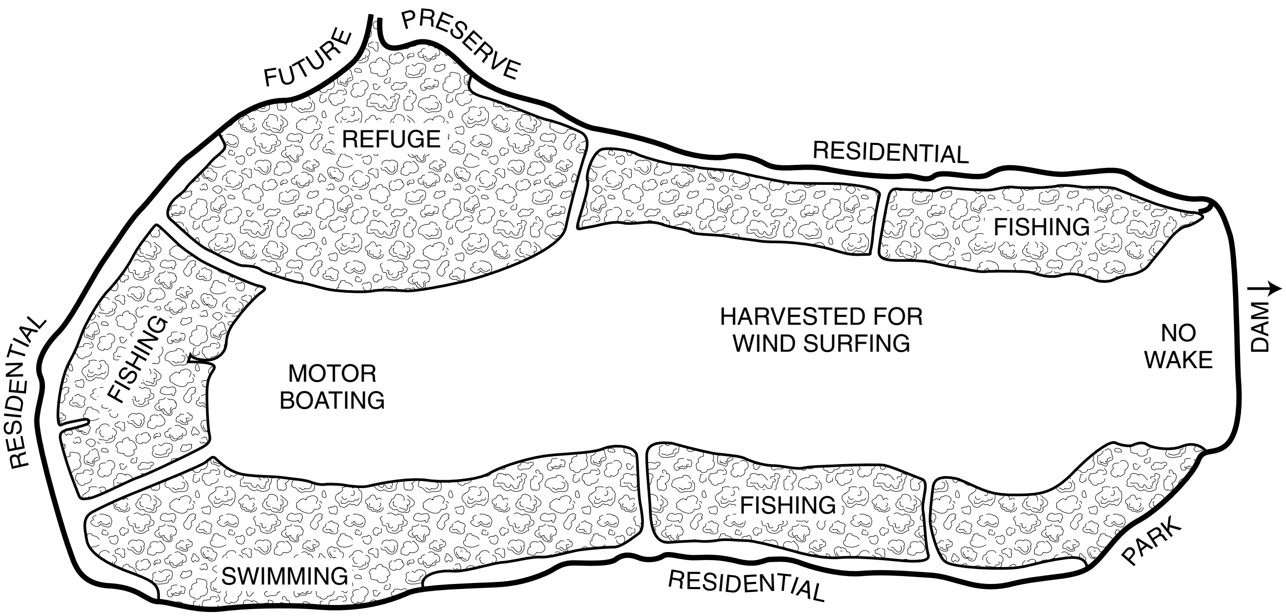


Figure 3. *Space and time zoning on hypothetical Legne Lake, showing plant cover and open water. (Diagram by Sandy Engel).*

for canoeing or sailing; and still others should be left alone. Some lakes could accommodate modest boating and wildlife, if lakeshore development can be controlled.

Classifying lakes for future development can assist lakeshore planning by designating how much and what kinds of development are appropriate for different waters. Within limits set by state law, local and county governments can control lakeshore development by classifying lakes for no development (“wilderness lakes”) or maximum development (“recreation lakes”). Between these extremes would fall lakes allowed wide lots and deep setbacks to preserve vegetative buffers and those allowed narrow lots and shallow setbacks with few areas left natural.

Lakes can also be classified by dominant sportfishes. Some lakes are best managed for black bass and panfish, others for walleye and muskellunge. Bass-panfish lakes can be further classified as bluegill-crappie lakes or yellow perch-northern pike lakes. Walleye and muskellunge lakes, in turn, can be classified by need for fish stocking or habitat protection. Lakes with unique habitat or fish species can form a separate class, such as cisco (*Coregonus artedi* Lesueur) or burbot (*Lota lota* [L.]) lakes. Some wilderness lakes entirely on public land can be classified as fish sanctuaries, where historical fish communities are protected from angling, boating, and fish stocking. Some seepage lakes can become “nursery lakes” for maintaining genetic strains of cisco, lake trout (*Salvelinus namaycush* [Walbaum]), or whitefish (*Coregonus clupeaformis* [Mitchill]).

Lakes can also be classified for boating, ranging from no boating allowed to boating limited only by state law. Between these extremes are lakes having motorboating limited to designated areas or speeds. Slow no-wake zones could reduce motor noise and boat wake for entire lakes larger than 50 acres, the current state limit (s. 30.635, Wis. Stats.), or specified distances from shore.

Lake classifications, like lakeshore planning, involve tradeoffs: protecting some lakes and lakeshores at the expense of others. As development pressures mount, such protection may be necessary to reduce noise pollution and keep lakeshore habitat for such wildlife as nesting ospreys (*Pandion haliaetus* [L.]) and common loons.

But lake classifications could bring unwanted boating and lakeshore development. Keeping boats off some lakes means more boating on other lakes; keeping walleye anglers off some lakes means more such anglers on other lakes. Mounting development and recreation pressures could force some lakes to be reclassified for narrower lots and smaller vegetative buffers, much as county governments grant variances for shallower home setbacks. Lake classifications may not slow development so much as redistribute it.

Habitat Enhancement

Planting vegetation on shore or in lake shallows can minimize lakeshore development effects. Aquatic plants can remove dissolved nutrients in runoff and protect the base of seawalls by blunting waves (Engel 1990). Cord grass (*Spartina alterniflora* Loisel) of Atlantic coastal marshes, resembling bulrushes along inland lakes, can reduce wave height by 71% and wave energy by 92% (Wayne 1976). Trees and shrubs can reduce flank erosion between seawalls, soil loss from freezing and thawing behind structures, and gully erosion on bluff tops from driving rain (Dai et al. 1977). Slump erosion of red clay along western Lake Superior, for example, was least on forested slopes where tree roots stabilized the soil (Davidson et al. 1989). A habitat fringe of vegetation thus can block soil erosion on shores with at least low to moderate wave energy.

Steep slopes can also be planted, though seedlings need protection from waves, runoff, and sloughing. Carpet rolls of native grasses, for example, stabilized steep slopes along north-central Wisconsin’s Rainbow Flowage: Native cord grass (*Spartina patens* [Aiton]) protected moist lower slopes whereas beach grass (*Ammophila breviligulata* Fernald) and sweet fern (*Comptonia peregrina* [L.]) protected dry upper slopes (Wendt 1994). Wooden pallets and biodegradable coir logs can help seedlings of native sedges (Cyperaceae) and rushes (Juncaceae) resist wave action and soil slumping (Goldsmith 1993, Santha 1994).

Vegetative buffers should be part of lakeshore plans and lake classifications. Buffers of grasses and other herbs (forbs) staked beside lake inlets have reduced initial sediment loads of 5,000 ppm by as much as 50%, depending on slope, velocity, plant species, and particle size (Karr and Schlosser 1978). Such vegetative buffers can incorporate *bioengineering* principles that not only stop erosion but also build a natural look to the shore (Gray and Sotir 1996).

Bioengineering uses synthetic stonework and interlocking blocks for natural color and contour, biodegradable fabrics for stabilizing slopes, and native plants for vegetative screens and habitat enhancers (Goldsmith 1991*b*, 1993; Wendt 1994). Shrubs like willows and dogwoods that root from stolons can be planted from rooted cuttings to hold soil on steep slopes (Oertel 1997). Brush layering and contour wattling can help form terraces to grow seedlings and shoot fragments (Wendt 1994, Gray and Sotir 1996). Artificial islands anchored to the lake bed can act as breakwaters to retard shore erosion and provide wildlife with habitat (Hoeger 1988), such as nesting islands for common loons and wood ducks. The shoots of bulrushes, cattails, rushes, sedges, and spikerushes are durable and elastic to absorb wave energy at the water's edge (Haslam 1978). Burlap or coir mesh staked or riprapped over these transplants eventually decay but prevent wave scour until shoots grow through the mesh and roots anchor the plants (Goldsmith 1991*a*, Santha 1994).

Adding riprap to the base of seawalls can improve biological habitat along developed shores by providing hiding and feeding crevices for invertebrates, young fishes, and tadpoles (Hylton and Spencer 1986). Consider the fish community of California-Nevada's Lake Tahoe, where plant beds are rare: Minnows, suckers, sculpins, and whitefish (Salmonidae) fed along natural boulder (>10 inches in diameter) or cobble-boulder (>2.5 inches) shores where prey was abundant but spawned on gravel shores where their eggs would be hidden in crevices from crayfishes (Beauchamp et al. 1994). Adult darters, sculpins, and smallmouth bass also prefer rocky areas devoid of plant beds as profitable feeding sites (George and Hadley 1979, Bryan and Scarnecchia 1992) and thus benefit from riprap.

Bottom fabrics can improve edge effect by creating fish nesting sites and cruising lanes. Bluegills use fiberglass screens to nest and guard yolk-sac fry (Engel 1984); largemouth bass lay eggs on nylon mats in hatcheries (Chastain and Snow 1966). Largemouth bass increase predation on bluegills when open lanes are made through plant beds (Engel 1990)—lanes that could be made with single or double strips of bottom fabric. Boat lanes could likewise be created by stretching bottom fabric from the base of riprap, seawalls, and piers to open water. Judicious use of bottom fabric, with riprap if needed for erosion control, could improve edge effect and thus habitat complexity, especially in dense monotypic vegetation.

Integrating riprap with modest densities of submersed plants can improve habitat for a variety of invertebrates and nearshore fishes. On exposed shores, wind-driven waves left unchecked can uproot aquatic plants to leave little shelter for prey fishes (Engel 1998). On quiet shores, submersed plants can become so crowded that piscivores cannot detect and pursue prey (Savino and Stein 1989); prey fishes then become abundant, slow growing, and even stunted (Crowder and Cooper 1982). Crowded plant stems can also reduce fish growth by impeding bottom feeding (Diehl and Eklöv 1995). Plant beds of modest density (about 10 stems/ft^2) or standing crop (0.2 oz dry weight/ft^2) strike the best balance between plant cover for invertebrate eaters, such as small bluegills, and swimming space for fish eaters, such as adult black bass (Wiley et al. 1984).

Because plants differ in feeding and nesting value, diverse foliage should be preserved around shoreline structures. Pumpkinseed sunfish caught more invertebrate prey in summer on round softstem bulrushes (*Scirpus validus* Vahl) than on large-leaf pondweed (*Potamogeton amplifolius* Tuckerman) (Dionne and Folt 1991). Structurally complex plant beds, with varied stem and leaf arrangements, increase refuge sites and feeding opportunities for plant-dwelling fishes. Openings and channels within plant beds increase edge effect that give large fishes access to plant-dwelling invertebrates and fry (Engel 1997). Even vertical stratification of plant foliage into basal, midwater, and canopy layers can add unique feeding opportunities (Engel 1990). A varied border of emersed, floating-leaf, and submersed plants—extending offshore from the base of riprap and seawalls—provides a better balance of fishes and plants than would riprap and seawalls alone.

Limiting new seawall construction, replacing crumbling seawalls with riprap, adding stone to the base of existing seawalls, planting vegetative buffers between structures, and using bioengineering principles to screen structures can minimize the cumulative effects of lakeshore development.

Management Recommendations and Research Needs

As more people develop lakefront property, lake managers and researchers will be challenged to find new ways of conserving lakeshore habitat and vegetative buffers between land and water. In the past 200 years, more than 80% of riparian corridors—deep vegetative buffers—have disappeared along rivers in North America and Europe (Naiman et al. 1993). That could happen to Wisconsin lakeshores, unless development can be curtailed or alternatives to controlling erosion gain wider support.

In administering their public trust doctrines, states have a responsibility for not only protecting lakeshores against excessive development but also producing comprehensive strategies that enhance biodiversity (Fischman 1997). That means more than curtailing new development through shoreland zoning and wise permit decisions: It means restoring abused lakeshores, guarding against cumulative effects, preventing fragmentation of vegetative buffers and sensitive areas, protecting lakeshores from invading species, and educating the public about biodiversity.

Managers need better criteria to evaluate whether a significant erosion problem exists. They need guidelines, especially during lakeside construction, on how to choose control strategies that minimize environmental harm yet remain cost effective. They also need examples of how bioengineering can integrate vegetation with lakeshore development or even replace traditional riprap and seawalls for erosion control. Most important, managers need guidelines on the cumulative effects of lakeshore development.

The relation between natural beauty and lakeshore development needs better definition, particularly the look of structures and the role of home setbacks, lot widths, and habitat zones (Macbeth 1992). Computer simulations, such as “virtual reality” software, can help design natural looking structures that blend with lakeshore plantings. Consumer attitudes toward shoreline structures, lakeshore vegetation, open space, and water quality need critical evaluation, especially on how much development can be tolerated before lakeshores no longer are judged natural or desirable. Educational programs should be expanded to inform people of development and nondevelopment options as well as how these options can be better planned.

Guidelines are needed on other ways to improve the natural look of developed lakeshores, the size and shape of lakeshore habitat, and the public awareness of conserving vegetative buffers. The Wisconsin Lakes Partnership—joining the DNR, University of Wisconsin-Cooperative Extension, and Wisconsin Association of Lakes—could form a shoreline management team to write guidelines on (1) building and repairing structures to blend with the landscape, (2) combining lake planning and transplanting techniques to improve fish and wildlife habitat along shore, and (3) expanding public education through “distance learning” that connects remote classrooms through closed-circuit television to a teaching center.

Priority research is needed on how native aquatic plants and riprap can be used alone or together to rebuild habitat along developed shores. Riprap and seawalls of different materials need to be evaluated to determine how these structures can best provide invertebrates, fishes, and higher vertebrates with sites to feed, hide, and breed. The ecological effects of riprap, seawalls, and piers could depend on whether aquatic plants grow near them, the lake bed is muck or stone, and habitats like marsh borders or woody debris are nearby. More research is needed on the effects of soft edge (lanes cut through plant beds) and hard edge (lanes of stone through plant beds): How can such lanes improve remaining habitat along developed shores?

Important gaps exist in understanding how lakeshore development affects the diet, growth, and survival of fishes, amphibians, and reptiles. Studies rarely proceed long enough or incorporate sufficient replicated controls to separate the effects of human disturbances from natural variations in weather. Few published studies on waterfowl disturbances separate effects of boating from lakeshore development, though loss of inshore habitat from development could force waterfowl to remain offshore where they would be exposed to boating noises and wakes. Studies on predation of shorebirds and burrowing mammals, such as meadow voles, seldom extend to the survival of raptors, especially owls and hawks, hunting such prey along lakeshores. Gaps remain in understanding both vegetative buffers as migration corridors and sensitive areas as habitat to feed, breed, and hibernate.

The value of riprap and seawalls for fish habitat needs more scrutiny. How do these structures affect the feeding success and food specialization of nearshore fishes? Well-designed studies on fish use of developed shores must consider daily and seasonal movements (Keast et al. 1978) as well as habitat switching (Werner and Hall 1979) by fishes. More studies are needed to identify plant species (Chick and McIvor 1994) and stem densities (Gotceitas 1990*a*, 1990*b*) that improve fish habitat and reduce lakeshore development effects.

Fish responses to shoreline development must separate habitat and water quality changes unrelated to development. Multivariate techniques, such as ordination and cluster analysis, can help distinguish such confounding influences on nearshore fishes (Hinch et al. 1991) and perhaps define trophic, habitat, and reproductive guilds as indicators of specific environmental changes (Balon and Chadwick 1979, Keast 1985, Fausch et al. 1990).

Many herpetological studies focus on single species and ignore interspecific competition, prey-predator interactions, and resource partitioning among overlapping populations. How different species, and ages within species, share habitat to bask, feed, hide, breed, and overwinter must be known to understand how habitat changes from lakeshore development affect amphibian and reptile communities. Plant loss, for example, could affect amphibians and reptiles indirectly through gradual food web and water quality changes.

Conserving fringes of lakeshore habitat may not be enough to reduce lakeshore development effects. Communities of waterbirds and mammals need ample plant habitat for diverse activities like brooding, feeding, loafing, and nesting; waterfowl need protection from boaters (Dahlgren and Korschgen 1992) and predators. Habitats must also be large enough to disperse breeding sites in spring and accommodate migratory ducks in fall. Setting aside offshore habitat zones (Kusler 1970, Engel 1989) and linking them through remaining vegetative buffers to upland habitat (Rogers 1996) could further reduce lakeshore development effects.

The cumulative effects of lakeshore development need better understanding and broader public awareness. Pier construction can increase motorboat activity, with added noise, water turbulence, and bottom scouring near shore. Seawalls with impervious surfaces replace soils that hold water and nutrients. Lakeside lawns increase nutrient input and replace ground cover near shore. With more boating inshore and no vegetation to blunt boat wakes, shoreline erosion worsens.

Education should be expanded to provide technical assistance for lakeshore buyers, real estate companies selling lake frontage, banks and loan associations financing land purchases, and local and county governments making zoning decisions. Education should also promote voluntary conservation to encourage responsible boating and land stewardship: More boaters need to respect lakeshore property and leave waterbirds alone; more riparians need to preserve vegetative buffers and leave erosion control to native plants. More brochures, bumper stickers, public talks, recorded messages, and workshops are needed. For example, a videotape on boating laws, ethics, and safety could help people renting personal watercraft. Such educational tools should target school curricula and children—our future riparians.

Local, county, and state governments must act fast, especially in northern Wisconsin, to purchase unspoiled lakeshores. A small tax on the sale of lakeshore property could fund a land bank to buy and restore lakeshore habitat. A lakeshore tax credit could encourage more property owners to keep natural shorelands intact and undeveloped. Public works projects are needed to demonstrate how lakeshores can be restored through bioengineering principles.

Citizens alone can save lakeshores from development. They can place deed restrictions on present and future use of their property, keeping it from being subdivided or further developed. They can buy remaining shoreland, saving that last plat of habitat for wildlife. They can install septic systems far away from lakeshores, so nutrients bind to soil before reaching lake water or ground water. And they can leave walks and driveways unpaved, to reduce impervious surfaces that funnel water and nutrients into lakes.

Acting alone, citizens can even restore natural lakeshores. They can plant native trees and underbrush along shore to reduce view corridors and enlarge plant buffers. They can protect native floating-leaf and submersed plants offshore. To reduce wave erosion, they can replace old seawalls and even bouldery riprap with border marsh—plantings bioengineered with degradable fabrics for a natural look.

Citizens working together can do even more. They can join lake associations to sponsor an annual “shore cleanup” for trash removal, form a “lake watch” against reckless boaters, and start a shoreline weed attack team (SWAT) for spotting invaders like rusty crayfish, purple loosestrife, and Eurasian watermilfoil (Engel 1992). Citizens can “spread the gospel” about lakeshore development through brochures, a “lake hotline” (telephone information service), and a lake website on the internet. They can also sponsor a “lake forum” to foster community pride through public talks about their lake. Money for such projects can be raised from banquets, fund drives, or, in Wisconsin, from taxes collected through a lake protection and rehabilitation district.

Researchers, managers, educators, and ordinary citizens must work closely with each other and with an informed public to curb excessive development, aesthetic loss, and ecological harm. Together, a lakeshore stewardship can be built to guide us into the next century.

Summary

1. The **legal basis of shoreline regulation** is embodied in statutes, administrative codes, and judicial decisions known collectively as the public trust doctrine. The state of Wisconsin holds navigable waters in trust for all its citizens and must consider the cumulative effects of small lakeshore alterations. Although riparians have the right to “reasonable use” of shorelines, documenting the cumulative effects of such use will be needed to curb rampant development.

2. With proper **design and construction**, riprap and seawalls can control shore erosion with little maintenance, provided chapter 30 of the Wisconsin Statutes and chapter NR 326 of the Wisconsin Administrative Code are followed. Shore sites may need grading and a bed of sand and gravel over filter cloth to ensure soil stability and drainage, though most vegetation is then destroyed. Pier construction leads to less direct shoreline damage but increases boating pressure that leads to plant loss and wildlife disturbance. Bottom fabrics smother underlying invertebrates but are site specific and can form channels in dense plant beds. Removing coarse woody debris robs fishes and waterbirds of feeding sites and exposes lakeshores to wave damage.

2. The **aesthetics** of riprap and seawall construction needs more careful survey. Many waterfront property owners desire “solitude and beauty” but disagree on how much lakeshore development is acceptable. They prefer vegetation to lakeshore development but differ in what types of development are offensive and how much development can be tolerated. Surveyors need to distinguish the attitudes of riparians living along developed shores from nonriparians and those living along less disturbed shores. Research is urgently needed on ways to minimize the aesthetic blight of some lakeshore development and encourage citizen involvement.

4. **Water quality** can deteriorate during and long after lakeside construction. Riprap and seawall installation can increase siltation and nutrient enrichment of lake water through erosion and debris fall. Soil erosion leading to nutrient enrichment can continue from wave scour at the base of structures and flank erosion between them. The increased nutrient input can fuel algal blooms that further reduce water turbidity. Water quality models that estimate nutrient input often do not consider development patterns, precipitation changes, and the cumulative effects of all development.

5. Woody debris creates **physical habitat** along lakeshores for invertebrates, fishes, and waterbirds. Removing the debris can directly damage nests and plants along shore, and it can indirectly expose lakeshores to wave scour and ice action that increase water turbidity. But the published studies we found did not consider competing habitat: Lakeshores crowded with plants or strewn with boulders can retain ample habitat after woody debris is removed.

6. Macroscopic plants create **biological habitat** that protects lakeshores from erosion and provides sites to bask, feed, rest, breed, and burrow. Riprap and seawall construction destroys plant beds directly through grading and backfilling slopes as well as indirectly through increased wave action and siltation. Integrating native plants into construction designs and protecting plants during construction can minimize habitat loss. Still, few published studies relate habitat loss to lakeshore development beyond site-specific changes. Piers, however, do shade underlying foliage and encourage motorboating that can scour the bottom and fragment plant beds beyond the piers. Weather-related water quality changes are often not separated from the effects of lakeshore development on plants.

7. **Macroscopic invertebrate** response to lakeshore development varies with the extent of habitat loss. More invertebrate refuge and feeding sites are found on riprap than on seawalls; piers and bottom fabrics create minimal invertebrate habitat. More plant habitat is destroyed during construction of seawalls than of riprap. Such habitat disturbance opens invasion sites for Eurasian watermilfoil that harbors fewer macroscopic invertebrates than do native plants like coontail and American elodea. Although substrate samplers provide a standard way to compare invertebrate responses over time, few such studies relate the samplers to the structures being simulated.

8. Most **nearshore fishes** spend at least part of their life cycle in shallow water and thus can be affected by lakeshore development: directly by habitat loss and indirectly by water quality change. Siltation and water turbidity increase during lakeside construction, impairing visual feeding of fishes and smothering eggs on lake bottoms. Some fishes can use piers for hiding and bottom fabrics for nesting. Replacing variegated riprap, rock outcrops, and woody debris with flat seawalls reduces the surface area for fish feeding and hiding. But we found few published studies that compare the habitat value of these structures or their use by nearshore fishes. Some species, such as darters and log perch, prefer cobble bottoms and thus could benefit from replacing at least the base of seawalls with stone riprap.

9. **Amphibians and reptiles** use lakeshores to bask, feed, nest, and overwinter. Lakeshore development can destroy plant cover and limit the size and number of breeding sites. Shore-dependent amphibians and reptiles are then exposed to bird and mammal predators. Painted turtles and snakes, for example, can still use riprap to bask but risk increased predation from raptors and mammals. Seawalls can limit access of such animals to water or hinder their return to land. But much of our knowledge of how amphibians and reptiles use lakeshores is anecdotal: We found no published studies comparing their use of developed and undeveloped shores for feeding and breeding.

10. **Waterbirds and mammals** need lakeshore vegetation and shore protection to feed, nest, and rest. Lakeshore development destroys the varied plants that many waterfowl need to mature and depletes construction materials for beavers and other furbearers. Waterfowl lose invertebrate prey that live on plants or underlying sediment. Cutting large forest tracts near shore concentrates breeding songbirds on fewer sites, putting the birds at risk from storms or predators such as raccoons and striped skunks.

11. **Mitigation and management** of lakeshore development starts with planning. Separate or integrated plans can be drafted to help protect and restore lakeshore habitat as well as to guide future development and avoid lake use conflicts between anglers, boaters, swimmers, and nature observers. Lakeshores can be planted with trees and shrubs for perching and nesting sites, with bulrushes and cord grass for blunting waves and reducing flank erosion, and with floating-leaf and submersed pondweeds for fish and invertebrate feeding and shelter. Lake classifications can assist lakeshore planning by defining appropriate levels of development and setting aside unspoiled habitat but may concentrate remaining development and recreation on fewer lakes. A bioengineering approach can help integrate lakeshore plantings with shoreline structures for a natural look to the shore.

12. Our **management recommendations** include expanded use of shoreland zoning to protect habitat loss and minimize the cumulative effects of clustered development. Lakeside construction guidelines should incorporate natural plantings to help screen structures like seawalls, boathouses, and lakeside homes. **Research needs** include control studies that compare fish and wildlife use of developed and undeveloped shores, creative uses for vegetative buffers, and new designs for shoreline structures.

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