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RESTORATION OF HUMAN IMPACTED LAND-WATER ECOTONES

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Abstract. Scientific perspectives and management techniques applied to land-water ecotones in three regions of North America are reviewed. In the Pacific Northwest, the Arid West, and the Laurentian Great Lakes, the riparian and nearshore areas have functions that make them unusually valuable for fish and wildlife, commercial or aesthetic considerations. The science and practice of resource management, however, differs strongly in quality and quantity among these regions. Small-scale conflicts of resource allocation have begun to be addressed through local legislation and management policies, but attempts to coordinate effective basin-level and regional management approaches are as yet poorly developed. Much basic information about the ecological role of riparian and nearshore habitats is required, as are methods to study and model land-water interactions at medium to large scales of time and space. It seems likely that in spite of some useful generalizations that may apply at continental or global scales, much of the most important management information will be formulated and calibrated on a regional scale.

Key words: ecotones, Pacific Northwest, Arid West, Laurentian Great Lakes, restoration.

INTRODUCTION

In this essay we outline approaches and limitations to the management and rehabilitation of land-water ecotones in our regions of expertise. Recent experience in North America shows that there is strong need for practical understanding of the ecologic role of these boundaries, and of the way that management techniques must recognize regional differences in that role. In particular, we focus on hydrology, geomorphology and vegetation, as they determine the structure, dynamics and economic importance of the land-water boundary. We will argue for management perspectives that foster recognition of key features of land-water ecotones, so that the ecological processes centered there may persist in a sustainable manner. Policy makers need a list of options locating the best opportunities for protecting land-water ecotones, and for restoring degraded areas back to a self-sustaining state by incorporating desirable, natural and designed features.

Our essay briefly examines these issues in three regions of North America, to illustrate differences in scientific perspectives, natural resource policy and practical management approaches applied to protection and restoration of land-water ecotones. In the **Pacific Northwest,** values related to migratory salmonids in forested, high-gradient, wood-dominated river systems are predominant; in the **Arid West**, grazing and agriculture on intensely managed, water-limited, erosional watercourses, highlight the importance of riparian vegetation; in the **Laurentian Great Lakes**, commerce and urban development focused on nearshore and river-mouth features, have resulted in basin-level rehabiliation initiatives to restore lost biotic, cultural and economic values of shorelines and tributaries.

Key ecological features of a land-water interface are not distributed evenly in space along the ecotone. Rather they are often localized areas of hydrologic stability and sediment deposition, as may occur at channel confluences, wide floodplains or river mouths. These areas change structurally through time, but show common characteristics regardless of whether they are

formed along the edges of rivers or lakes. The most important of these characteristics are extensive surface and subsurface hydrologic connectivity of the ecotone with the adjacent upland and aquatic systems; diverse vegetation represented by a variety of age classes; and resilience in the response to changes in the hydrologic and geomorphic characteristics of the boundary.

The science and management of riparian resources seems most developed in the Pacific Northwest, and this is where we are best able to provide practical detail. The other regional examples illustrate the exciting conceptual parallels and management innovations that are being applied in widely divergent landscapes of North America.

RIVERINE RIPARIAN ZONES IN FORESTED AREAS OF THE PACIFIC NORTHWEST

Regional Features

From an ecological perspective, riparian zones along rivers can be defined functionally as three-dimensional zones of direct interaction between terrestrial and aquatic ecosystems (Figure 1). The boundaries of riparian zones, as defined from this perspective, extend outward from the channel to the limits of flooding and upward into the canopy of streamside vegetation (Meehan et al. 1977, Swanson et al. 1982). Dimensions of a zone of riparian influence vary in relation to the dynamics of particular processes of interest. For example, in a coniferous forest, the zone from which large woody debris could enter the active channel or floodplain may extend farther away from the stream than the zone from which leaves and needles would be contributed. The zone of shading influence may be asymmetrical, depending on stream orientation, latitude, and topographic shading. In the Pacific Northwest, the riparian three-dimensional zone occupies an area of less than 5 percent of the total landscape.

Development of an ecosystem perspective of riparian zones must incorporate the complex array of physical, chemical, and biological interactions that occur within the interface between aquatic and terrestrial ecosystems. Of key importance here is the geomorphic context that valley floor landforms provide for riparian zones. Stream reaches are delineated by the type and degree of physical constraint imposed by the valley wall. The degree of constraint controls local geomorphic processes, and therefore influences terrestrial and aquatic communities through erosion, sedimentation, soil movement and other disturbance mechanisms.

Constrained reaches in which the valley floor is narrower than two active stream channel widths are formed where bedrock, landslides, alluvial fans, or other geologic or human-produced features constrict the valley floor, and thus limit lateral mobility of the channel. Streams within constrained reaches tend to be relatively straight, single channels with limited lateral heterogeneity. During high flow, the position of the constrained stream channel is relatively fixed within narrow floodplains and stream power increases rapidly with increasing discharge. Relative resistance to erosion affects the persistence of the constraint and the composition of the substrata in the active channel. Valley floors in constrained reaches are characteristically narrow and include few geomorphic surfaces within the valley floor. Riparian vegetation in these areas is usually similar in composition to adjacent hillslope plant communities.

Unconstrained reaches occur in areas in which the valley floor is wider than two active channel widths affording some lateral mobility to the channel. Streams within unconstrained reaches tend to be complex, multiple channels with diverse ecotonal heterogeneity. During floods, the positions of the unconstrained stream channel is dynamic within the floodplain and stream power can dissipate by flooding over numerous geomorphic surfaces within the valley floor with increasing discharge. There is stream bank and bed erosion in these dynamic areas. Riparian vegetation in these

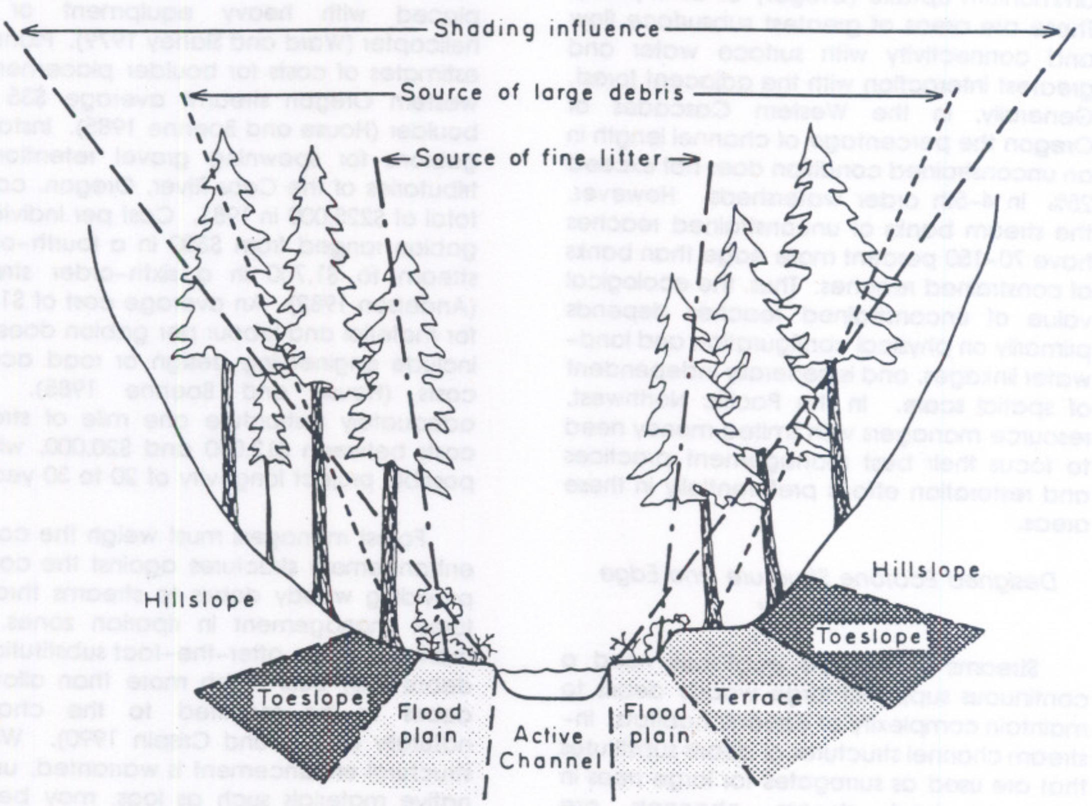

Figure 1. Cross-sectional view of valley landforms and associated riparian plant communities, illustrating varying zones of terrestrial influence on aquatic ecological processes (modified from Gregory et al. *in press*).

areas is diverse both in terms of species composition and age classes within a species.

Unconstrained reaches in the Northwest region of North America are ecological "hotspots." They are areas which retain organic materials, have much greater algal primary production, have the highest densities and diversity of fishes, greater aquatic invertebrate densities, and much greater microbial activity as indicated by ammonium uptake (Gregory et al. *in press*). These are areas of greatest subsurface flow and connectivity with surface water and greatest interaction with the adjacent forest. Generally, in the Western Cascades of Oregon the percentage of channel length in an unconstrained condition does not exceed 25% in 4-5th order watersheds. However, the stream banks of unconstrained reaches have 70-150 percent more edge than banks of constrained reaches. Thus, the ecological value of unconstrained reaches depends primarily on physical configuration and land-water linkages, and is generally independent of spatial scale. In the Pacific Northwest, resource managers with limited money need to focus their best management practices and restoration efforts preferentially in these areas.

Designed Ecotone Structure and Edge Complexity

Streams in forested ecotones need a continuous supply of large woody debris to maintain complexity of aquatic habitats. In-stream channel structures or debris substitutes that are used as surrogates for large trees in ecotones and stream channels are conceptually popular with both timber and fisheries managers. The fisheries enhancement programs of many agencies emphasize construction of boulder berms, gabion structures of various configurations, boulder clusters, side channels, and off-channel ponds as primary techniques for habitat improvement on stream channels. Stream habitat enhancement projects on the west coast have improved spawning and rearing habitat for salmonids and probably increased fish production in some areas. However, rigorous ecological evaluation of such projects is rarely undertaken to verify benefits.

Economic analysis of enhancement projects shows that substituting other structures for large woody debris can be expensive. The cost of placing individual boulders in the Keogh River, of British Columbia for example, was $22 to $24 per boulder (in 1977 Canadian dollars), depending on whether the boulders were placed with heavy equipment or by helicopter (Ward and Slaney 1979). Planning estimates of costs for boulder placement in western Oregon streams average $35 per boulder (House and Boehne 1985). Installing gabions for spawning gravel retention in tributaries of the Coos River, Oregon, cost a total of $225,000 in 1981. Cost per individual gabion ranged from $300 in a fourth-order stream to $1,700 in a sixth-order stream (Anderson 1982). An average cost of $1,200 for material and labour per gabion does not include engineering design or road access costs (House and Boehne 1985). To adequately restructure one mile of stream costs between $12,000 and $20,000, with a possible project longevity of 20 to 30 years.

Forest managers must weigh the cost of enhancement structures against the cost of providing woody debris to streams through forest management in riparian zones. In many instances, after-the-fact substitution of debris may cost much more than allowing debris to be recruited to the channel naturally (House and Crispin 1990). Where structural enhancement is warranted, use of native materials such as logs, may be the most cost-effective means of achieving the hydraulic diversity necessary for productive fish habitat (Lisle 1982).

Another problem with fisheries programs designed around enhancement structures is the general difficulty in finding suitable construction sites. From a logistic standpoint, not all stream miles could be improved with enhancement devices even if unlimited funding was available. For example, one

Bureau of Land Management District in Oregon has 528 miles of streams producing anadromous fish, and only 60 miles are feasible for structural rehabilitation. Approximately 90 percent of the stream miles cannot be "artificially" rehabilitated because of access problems and other constraints, and must be managed for vegetative diversity in forested ecotones to maintain acceptable levels of fish production.

Enhancement structures are going to be placed in streams at an accelerated rate into the 1990's. Although structural additions and alterations may improve habitat in streams lacking physical diversity, they cannot replicate the dynamic physical interactions between water, sediment and riparian vegetation. Structures are usually a short-term solution, and are implemented in the absence of a long-term watershed improvement plan.

In forested basins, comprehensive watershed planning must call for reestablishment of woody vegetation and accelerated growth of trees, to provide snags and wood to the stream. Such silvicultural management programs must be key components of fish and wildlife habitat improvement programs, but silvicultural prescriptions designed to grow streamside vegetation are neither widely used nor well understood. Natural riparian forest can foster structural diversity by providing dead wood, varying canopy heights, and a varied vegetative community. However, maintaining biological diversity and habitat for fish and wildlife species involves much more than stream-side strips of riparian vegetation. Research can tell us how various tree species, root systems and debris sizes function through time in channels of different widths, gradients, and valley form. Such information is necessary to aid decisions regarding where, what kind, and how many trees are to be selectively planted or maintained in riparian areas to optimize ecotone structure and function over the long term. Management policies and practices are needed that will allow riparian vegetation to maximize its beneficial effects upon the hydrology and channel morphology of stream and lake ecosystems.

Basin Planning for Maintenance of Ecological Hotspots

The movement of water and sediment downwards through a drainage network translates detrimental effects of forestry off-site and into aquatic environments. In the Pacific Northwest, with its steep terrain and high precipitation, spatial and temporal patterns of runoff and soil movement are important in determining the extent and severity of aquatic habitat degradation. New techniques allow areas with high rates of natural sediment production from debris slides or earth flows to be identified within a drainage basin, so that careful basin planning can minimize damaging effects of forestry operations on fishery resources (Megahan and King 1985, Sidle et al. 1985, Swanston 1985). In areas with high relief and abundant stream channels, knowledge of the movement of debris flows through drainage networks allows managers to maintain the structure and function of ecological hotspots along stream edges (Benda 1985, Swanson et al. 1987).

Standards and Guidelines for Riparian Management Areas in the Pacific Northwest

The important functional role of riparian forests in providing trees to streams and rivers has been recognized by land managers in the western United States (Bisson et al. 1987, Sedell et al. 1988). All western state and federal jurisdictions have adopted standards for leaving large trees in riparian zones to protect fish and wildlife. However, management schemes to maintain diverse ecotones in the Pacific Northwest have been difficult to develop because of conflicting resource demands in riparian areas and the shortage of information on silvicultural management strategies for riparian zones.

Most streamside management schemes incorporate an un-harvested buffer strip of trees along the stream channel. The width of the buffer, and the age and abundance of its trees are important ecologic and economic concerns. Reduced harvest frequency in riparian zones may protect important riparian functions, by increasing average tree age. Large, old wood is required in stream channels to provide structural complexity and aid in formation of pools and complex channel edges. Further, the diameter and length of wood must increase with increasing stream size to be effective in formation of good fish habitat. Most National Forests in western United States have planned some form of double rotation scheme for stream ecotones. The rationale for a double rotation comes from the fact that large wood >30 cm in diameter is required in stream channels to provide structural complexity and aid in formation of pools and edge complexity. Woody debris at least 60 cm in diameter and 13 m in length is required on coastal streams with widths greater than 10 m. Wood recruitment studies by Grette (1985), Long (1987) and Heinman (1988), indicate that large coniferous debris does not enter streams in significant amounts until the stand age reaches 120 to 150 years.

Studies that integrate riparian silvicultural strategies for fish habitat considerations are rare. A study by Rainville et al. (1985), however, attempted this kind of integration for the Idaho Panhandle National Forest. The investigators linked stream habitat inventory information and silvicultural data and developed a computer simulation model to evaluate the effect of silvicultural practices on the potential recruitment of large wood pieces to stream channels. Forest habitats of western hemlock (*Tsuga heterophylla*), grand fir (*Abies grandis*), and subalpine fir (*Abies lasiocarpa*) were analyzed. Active management was clearly essential to maximize stream habitat complexity and fisheries resources in these vegetative habitat types.

The "postage stamp" entry technique of Rainville et al. (1985) where 200 m long blocks are clearcut in ecotones is a marked contrast from the forest practice rules of Oregon and Washington, and the general guidelines used in the National Forests of the Pacific Northwest and Alaska, which generally call for a selective harvest of large trees in forested ecotones. The selective harvest approach would ideally leave a stream with a canopy of diverse vegetative structure and species along its entire length. The postage stamp approach optimizes fish habitat structure over the entire basin, and requires a detailed basin harvest and silvicultural plan.

The cost of leaving economically valuable timber in the ecotone varies as a function of tree abundance, but is usually relatively less expensive than equivalent upland reserves. In general, the densities of large conifers in forested ecotones are 70% of upland densities and basal area in the western Cascades (Tom Spies, *personal communication*) and 15 to 50% of the densities and basal area in the Oregon Coast range (Oregon State Department of Forestry 1987, Andrus and Froehlich 1988). If all of the 3rd order fish-bearing streams in the upper Willamette River basin were protected by not harvesting large conifers within 30 m of the stream edge, the resulting loss of available timber in the basin would amount to only 0.3 percent.

House and Crispin (1990) did an economic analysis of the value of large wood debris from the ecotone forest to salmonid habitat in coastal Oregon streams. They showed that the fisheries benefits of maintaining conifers in the ecotone at a high rate of wood loading levels were calculated to 11 percent greater by year 20, and 59 percent higher after 94 years (an increase of over $50,000 in present value per kilometer of stream) over the stump value of the conifers in the ecotone. Management scenarios for structural stream rehabilitation versus managing for conifer densities in the ecotone showed greater short term values for structural rehabilitation efforts. However, long term economic benefits of rehabilitation management were substantially less than for those streams managed under continuous high debris loading.

RIPARIAN ECOTONES IN ARID AND AGRICULTURAL LAND

Many groundwater aquifers associated with river channels in the western United States are maintained by infiltration of upland runoff. These alluvial aquifers are an important source of water for human use and for riparian vegetation. Water storage in such aquifers was once partially responsible for maintaining baseflow in western rivers, many of which are now dry during much of the year. Removal of riparian vegetation has been responsible in part for the change from perennial to intermittent flow in some of these rivers (McNatt 1978, Elmore and Beschta 1987).

Riparian Values and Management

Figure 2A provides a cross-sectional view of a small, degraded stream system in an arid landscape. In this example, the stream has cut down through previously deposited alluvium. As a result, the channel and associated vegetation have changed dramatically. Plant species typical of wetland conditions have largely disappeared and the channel continues to erode laterally. There is little subsurface storage of water and the stream is characterized by intermittent flow.

In contrast, Figure 2B illustrates a previously eroded channel that supports a diversity of riparian vegetation and has undergone recovery. The vegetation provides relative stability to stream banks and causes deposition of sediment. Over time the channel undergoes aggradation. Such aggradation is often a natural consequence of allowing streamside vegetation modified by grazing, logging, agriculture or other management practices, an opportunity to recover. A consequence of this aggradation process is that the water table will similarly rise. In some cases, a formerly intermittent stream may flow perennially.

Agriculture and management of riparian vegetation for erosion control can be compatible along floodplain systems. For centuries, native American and Spanish American farmers of the arid Southwest have managed riparian vegetation adjacent to their agricultural fields (Nabhan 1985). They planted, pruned, and encouraged tree species for flood erosion control, soil fertility renewal, buffered field microclimates, and fuel wood production. Living fence rows were constructed by weaving brush between the trunks of lines of cottonwood, willow, and mesquite adjacent to their floodplain field. This woven fence slowed lateral flood waters without channelizing the primary streambed the way in which concrete or riprap channel banks would. As a result, when summer or winter floods covered a floodplain terrace, channels are less likely to become entrenched and erosion is less pervasive than with a barren floodplain (Nabhan 1985).

Streamside vegetation also maintains and enhances water quality in streams draining agricultural lands (see Correll this volume). In the midwest and southeastern coastal plain, woody riparian vegetation not only stabilizes banks and creates complex fish habitat, but it also filters nutrients and maintains water quality on agricultural watersheds. The removal of nutrients such as nitrogen and phosphorus occurs via several mechanisms (Lowrance et al. 1985, Petterjohn and Correll 1984): (1) surface filtration of sediments, (2) incorporation of N and P into living woody plants; and (3) nitrification-denitrification processing below ground and at the soil surface. Soils of the riparian ecosystem present ideal conditions for denitrification: high organic matter from input of forest litter; seasonal waterlogging; and large inputs of nitrates in subsurface flow. Most of the nitrogen goes to the atmosphere as gas via denitrification with only a small amount incorporated into the biomass of the growing trees. In Maryland, a 15 m buffer-strip of trees is required between agricultural land and the Chesapeake Bay and adjacent tributaries. This width of a filter strip can remove more than 75 percent of the ground water nitrogen and more than 40 percent of the phosphorus before it gets into the adjacent stream or water body.

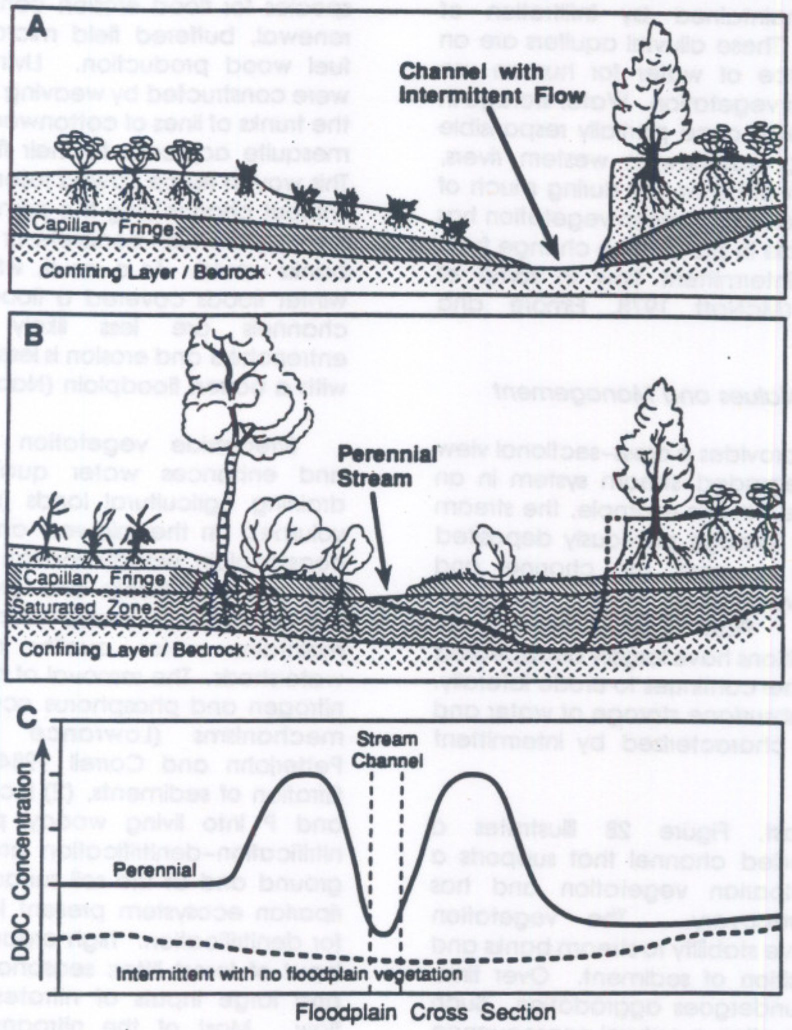

Figure 2. General characteristics and functions of riparian areas in arid lands (from Elmore and Beschta 1987). (A) Degraded riparian area with very little surface and subsurface water connectivity and no vegetation interaction with the stream. (B) Recovered riparian area with increased connectivity of subsurface and surface water, vegetation stabilized banks and extensive interaction with diverse vegetation. (C) Dissolved organic carbon (DOC) concentrations in floodplain groundwater, along transects for perennial and intermittent streams.

Currently trees in ecotones of arid lands play a limited role in agriculture. Benefits derived from a dense, deep-rooted tree buffer strip may include:

1. Production of a woody crop entirely useful as a renewable fuel or pulp wood.

2. Roots and root exudates will place more organic carbon deeper in the riparian zone soil profile (Figure 2C). Theoretically, an increased amount of organic carbon affects pesticide concentrations in groundwater by increasing the rate of pesticide degradation by microbes within the soil profile.

3. Biological diversity enhanced by habitat restoration. Fish and wildlife habitat is usually highly fragmented in agricultural watersheds. Restoration of corridors linking alternative habitats will enhance the health of both aquatic and terrestrial organisms.

The economic value of forested riparian corridors in floodplains of the agricultural midwest has been recently addressed by Lant and Tobin (1989). They illustrate how an economically efficient mix of woody riparian corridors and cropland can be estimated and they suggest how such a mix of land uses can be encouraged through appropriate agricultural policies (i.e. economical incentives). They also emphasize that the location of riparian wetlands and corridors within an agricultural watershed greatly influences their effectiveness in providing the environmental services discussed above.

The placement of riparian forest corridors in agricultural land will often be dictated by planning for flood control, sediment control, groundwater management and recreational benefits. In the longitudinal dimension, riparian forests cannot directly impact flooding and water quality upstream of their occurrence, and their influence will gradually diminish in a downstream direction. Thus, riparian forests and wetlands in lower reaches of the fluvial system, or directly upstream of valued recreation areas or reservoirs, may provide more benefits than similar sized riparian forest or wetlands elsewhere in the watershed (Johnston et al. 1990). In the lateral dimension riparian forests adjacent to the riverbank or in areas of high probability of flooding will have the greatest beneficial impact on water quality and flooding.

SHORELINES IN GREAT LAKES ECOSYSTEMS

The shorelines and watersheds of the Laurentian Great Lakes have been divided between the Province of Ontario and the States of Minnesota, Wisconsin, Illinois, Indiana, Ohio, Pennsylvania and New York. More than 36 million people live in the Great Lakes basin, and are concentrated in a southern megalopolis comprising the cities of Chicago, Detroit, Toledo, Cleveland, Buffalo, Hamilton, Toronto, Rochester, and others. The southern shores and tributaries, along Lakes Michigan, Erie and Ontario, have been widely restructured and degraded in the face of extensive urbanization and industrialization. In the north, Lakes Huron and Superior are sparsely populated, with development and industrialization concentrated along a few large bays and river mouths.

The ecological characteristics of riparian and nearshore ecosystems in the Great Lakes are analogous in many ways to marine systems such as the Baltic Sea for large-scale features (Regier et al. 1988), and to inland lakes and rivers, for small-scale features (Steedman and Regier 1987). Governance and management of Great Lakes land-water ecotones is complicated by the large number of federal, state/provincial, regional and municipal agencies with mandates relevant to riparian land, navigable waters, conservation, environmental protection, fisheries and wildlife. The binational and regional approaches that have been developed for the protection, rehabilitation and management of Great Lakes land-water ecotones are among the most ambitious and complex that have been attempted for such a resource.

Regional Ecosystem Features

Key habitats.–Certain locales or habitats along the land-water ecotone may be more important than others to the health and survival of Great Lakes aquatic ecosystems (Steedman and Regier 1987). Relatively small or localized areas that provide essential conditions for breeding, spawning, rearing, and feeding of fishes may have an ecological role far more important than would be suggested by their size alone. In temperate aquatic ecosystems such as the Laurentian Great Lakes, these "centers of organization" tend to occur in the coastal or nearshore areas, and exhibit distinctive combinations of abiotic and biotic characteristics.

In the Great Lakes Basin, the structural and hydrologic features of river channels, coastlines, rocky shoals, estuaries and coastal wetlands are such that in a natural condition: 1) substrate and sediment accumulations are of a size and arrangement that either provides clean, well oxygenated substrate surfaces and interstices, and/or sediments suitable for the establishment of aquatic plants; and 2) disruptions by currents, wave action, ice movement, seiches or floods are of a frequency, intensity and predictability that allows a variety of plants and animals to colonize the area, either for vulnerable embryonic or juvenile stages, or for the entire life cycle. With respect to native, valued species of Great Lakes fishes, the most important requirements of the early life stages, i.e. provision of oxygenated water and protection from predation, are best met in these habitats.

Quantity and Quality of Great Lakes Land-Water Ecotones.–In urbanized areas of the Great Lakes there has been widespread destruction of nearshore and tributary structural features through activities such as shoreworks, channelization, land clearing, landfilling, land drainage, rock removal, dredging, and siltation. The remaining locales that seem to function as ecological "centers of organization" are indeed becoming identifiable as discrete and often isolated entities, probably much more so than would have been the case 200 years ago when such features dominated much of the Great Lakes nearshore ecotone.

The destruction of coastal wetlands, once widespread on the lower Great Lakes, serves to illustrate this point. Most authorities estimate that about two-thirds of those wetlands have been filled or drained for agricultural, industrial and urban development (Patterson and Whillans 1985, Conservation Foundation and Institute for Research on Public Policy 1989). Whillans (1984) summarized physical characteristics of the Canadian shoreline of the Great Lakes (Table 1) and found that only about 30% overall of the Canadian shoreline provides sheltered embayments or estuaries which may support wetland development and growth of aquatic plants. The rest of the shoreline is relatively exposed and wave-swept, but may have important features such as gravel beaches or bedrock shoals required for spawning of salmonids and coregonids. Shoals large enough to be mapped on navigational charts are surprisingly rare even on the rugged shorelines of Lake Superior and Lake Huron.

Information about the quality, distribution and ecological importance of wetlands and other key shoreline habitats is being gathered by provincial and state agencies to facilitate protection and rehabilitation. This information has not yet been compiled and mapped on a basin scale, although steps have been made in that direction (Patterson and Whillans 1985, Botts and Krushelnicki 1988).

With regard to potential use by valued fish species, some broad-scale indication of the ecological nature of Great Lakes tributaries may be available through the Great Lakes Fisheries Commission, as part of their sea lamprey control program. The sea lamprey (*Petromyzon marinus*) feeds on a

Table 1. Physical characteristics of Great Lakes Shoreline (Canadian side only) (Whillans 1984)

SHORELINE LENGTH (km)

Shoreline Type	Ontario	Erie	St. Clair	Huron	Superior	Total
Exposed	472	493	47	1254	936	3202
Embayment	68	107	20	396	106	697
Estuary	29	1	5	265	49	349
Protected (Manmade)	35	47	61	49	36	228
Total	604	648	133	1964	1127	4476
No. of Shoals	34	19	25	339	67	484

variety of valued fish species, and is the object of a multi-million dollar control effort on the Great Lakes. The sea lamprey spawns in certain streams and rivers tributary to the Great Lakes, and in some nearshore areas off large river mouths. Streams that support larval lamprey are generally suitable for spawning by "anadromous" salmonids, by virtue of migratory access, cool temperatures and good water quality. Of approximately 5747 streams tributary to the Great Lakes (Table 2), only 433, or 7.5%, are known to have supported sea lamprey since 1957 (Mormon et al. 1980). Of these, 364 are on the upper Lakes (Superior, Huron, Michigan), and 69 are on Lakes Erie and Ontario. In spite of the large number of tributary streams on the Great Lakes, waters suitable for reproduction and rearing of valued fish species may be relatively rare. If one assumes that the average width of a river mouth on the Great Lakes is 0.1 km, then approximately 570 km or 3.4% of the Great Lakes shoreline is "riverine." If one further assumes that use of a river by sea lamprey denotes the presence of salmonid habitat, then only 43 km or 0.25% of the Great Lakes shoreline provides access to high quality habitat for riverine salmonids.

Rehabilitation techniques for Great Lakes Land-Water Ecotones

Techniques and feasibility of ecosystem rehabilitation in nearshore waters of the Great Lakes were examined in detail at a 1979 workshop in Toronto, Ontario, convened under the auspices of the Great Lakes Fisheries Commission. Here, rehabilitation connotes a pragmatic mix of restoration, enhancement, remediation, mitigation and preservation, to benefit highly valued, sensitive uses of Great Lakes ecosystems. Approximately 50 recognized experts in the natural science and engineering of ecological rehabilitation pooled their ideas to produce the synopsis documented in Francis et al. (1979). That synopsis, while too lengthy to include in this volume, represents one of the most comprehensive and detailed listings of practical rehabilitation techniques compiled for the Great Lakes, and should be examined by readers interested in further detail.

Francis et al. (1979) listed 18 human-caused ecological stresses in Great Lakes ecosystems; of these 18 stresses, 11 are clearly relevant to a consideration of nearshore or coastal degradation, and are listed in Table 3. Although the synopsis of Francis et al. (1979) is now more than ten years old, it appears to have stood the test of time, particularly with regard to major institutional rehabilitative efforts. A contemporary workshop to address these issues would probably provide a number of innovative ideas and approaches to ecosystem rehabilitation, most likely with regard to handling and treatment of toxic substances. However, most of the approaches to structural rehabilitation and remediation of conventional pollution would be substantively similar.

It was not possible to estimate rehabilitation costs in 1979; this is likely still the case. Nonetheless, Francis et al. (1979) reached two conclusions which are still valid. First, a great deal is not known about the benefits and costs of rehabilitation measures. Second, it is readily apparent that some degree of rehabilitation will be highly beneficial to all users of the Great Lakes and their ecotones.

Remedial Action Plans on the Great Lakes

The Great Lakes Water Quality Agreement of 1978, amended in 1987 (International Joint Commission 1988), provides a key binational vehicle for rehabilitation and restoration of land-water ecotones on the Great Lakes. Under the Agreement, the Federal governments of Canada and the United States, in cooperation with provincial and state agencies, committed to develop and implement Remedial Action Plans (RAPs) for 42 Areas of Concern on the Great Lakes and their connecting channels (Figure 3). Areas of Concern were defined as locations, usually heavily industrialized river mouths or embayments, where environmental

Table 2. Great Lakes shoreline lengths and tributary counts.

Lake	Shoreline Length (km)[1]	Number of Tributaries[2,3,4]**	Stream km below first barrier (Canadian only)[5]
Superior	4385	840	1091
Huron	6157	1654	1720
Michigan	2633	447	
Erie	1402	558	259
Ontario	1146	507	246
Canadian Shoreline U.S. shoreline		2860 1662	33164
Total	17017*	5747	

* includes connecting channels
** different subtotals from different authorities

[1]Botts and Krushelnicki (1988)

[2]Lawrie and Rahrer (1973)

[3]Mormon et al. (1980)

[4]Christie (*personal communication*)

[5]Bird and Rapport (1986)

Table 3. Ecological stresses active in nearshore or coastal areas of the Laurentian Great Lakes (Francis et al. 1979).

1. Microcontaminants: toxic wastes and biocides
2. Nutrients and eutrophication
3. Organic inputs and oxygen demand
4. Sediment loading and turbidity
5. Stream modification: dams, channelization, logging and changes in land use
6. Dredging and mineral, sand, gravel and oil extraction
7. Filling, shoreline structures, offshore structures
8. Water level fluctuation and control
9. Dyking and hydraulic modifications of wetlands
10. Thermal loading
11. Major degradative incidents or spills

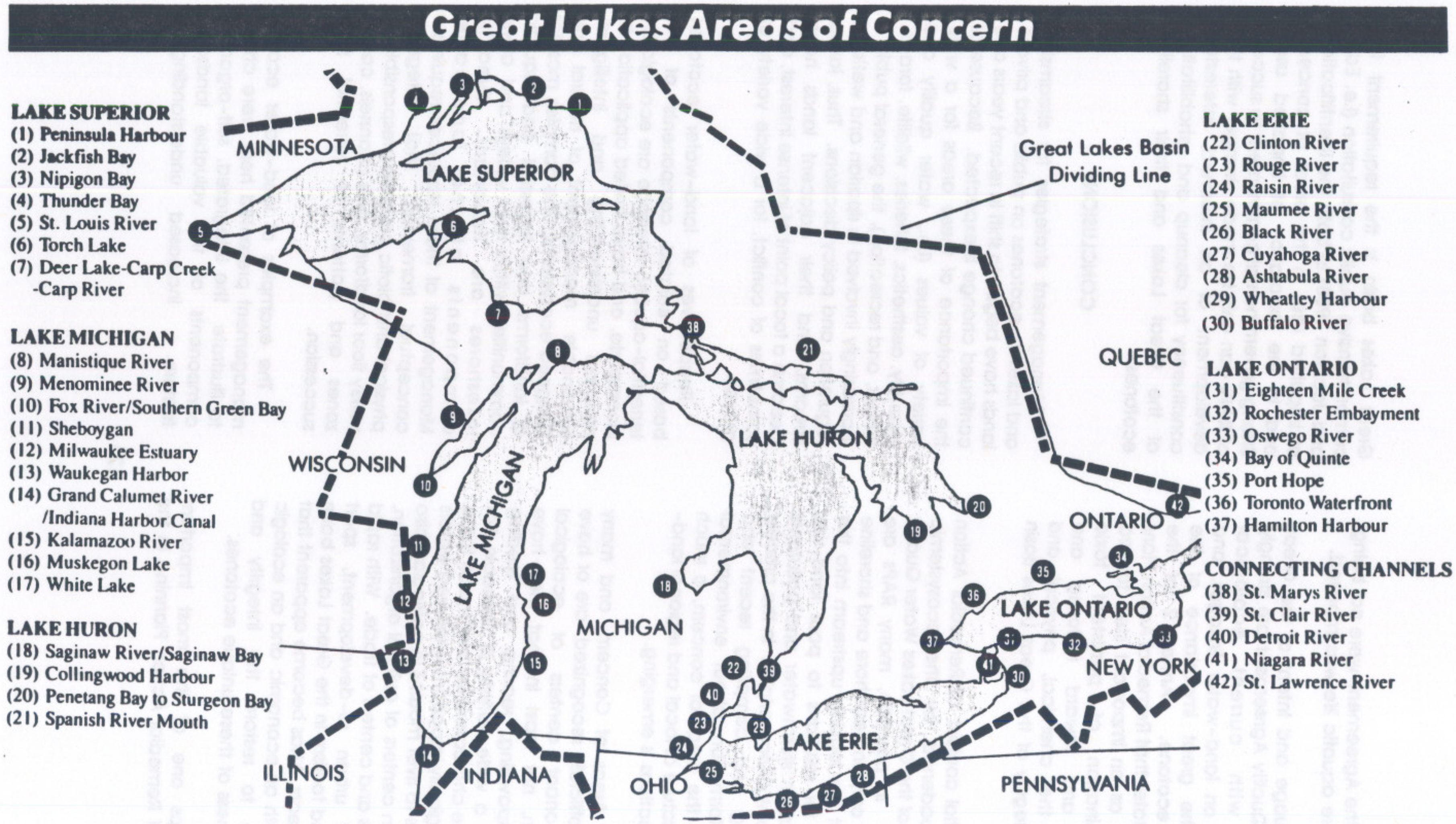

Figure 3. International Joint Commission "areas of concern" in Laurentian Great Lakes coastal ecotones (map courtesy of The Great Lakes Reporter, The Center for the Great Lakes, Chicago, Illinois).

objectives of the Agreement were not being met and where aquatic life was impaired.

The language and intent of the Great Lakes Water Quality Agreement are strongly consistent with current ecological perspectives on land-water linkages, and emphasize the great importance of the land-water ecotone. Annex 2 of the Agreement states that Remedial Action Plans are to serve as an important step toward virtual elimination of persistent toxic substances, and toward restoring and maintaining the chemical, physical and biological integrity of the Great Lakes Basin Ecosystem.

The spatial context of Remedial Action Plans is broadened by the ecosystemic perspective of the Great Lakes Water Quality Agreement. In practice, many RAPs are focusing not only on nearshore and shoreline habitats, but are looking upstream into the watersheds for solutions to poor land-use practices, urban stormwater and pollutants with non-point source origins. In the process of gathering and compiling recent and historical information about environmental problems in the areas of concern, a much improved picture of local and regional land-water interactions is emerging.

The 42 Areas of Concern, and many others not officially recognized, are or have been important centers of ecological organization, not least in that they have provided spawning, rearing and feeding habitat for a wide variety of desirable fish species. The characteristics that made these areas biologically important (sheltered waters and access to river mouths in particular) also made them centers of cultural organization, as harbours and centers of trade. With rapid growth of urban re-development, sport fisheries and tourism in the Great Lakes basin in recent years, it has become apparent that there is both an economic and an ecologic imperative to restore the integrity and attractiveness of these unique ecotones.

Perhaps one of the most important aspects of Remedial Action Planning in the Great Lakes basin is the requirement for comprehensive public consultation (i.e. Eder and Jackson 1988) in both the identification of impaired uses in the areas of concern, and in the restoration of impaired uses. Strong governmental commitment to success of RAPs can only be made stronger with the development of an informed, interested constituency for cleanup and rehabilitation of the Great Lakes and their shoreline ecotones.

CONCLUSIONS

Management strategies for streamside and lakeside ecotones on public and private lands have begun to shift in recent years and continued change is expected. Because of the importance of these areas for a wide variety of values (i.e., water quality and quantity, aesthetics, fisheries, wildlife, forage, timber, and recreation), the general public is increasingly involved in riparian and wetland regulation and policy decisions. Thus, lakes, streams, and their adjacent lands have become a focal point of intense interest, and sometimes of conflict, for a wide variety of groups.

Perspectives of land-water ecotones based on isolated components of the terrestrial-aquatic interface are ecologically incomplete, and have limited application to practical understanding and intelligent, sustainable management of natural and designed ecosystems. The complex mosaics of landforms and terrestrial and aquatic communities within river valleys and along lakeshores are important, dynamic components of the landscape. Management of these resources requires a conceptual framework that integrates physical and biotic processes responsible for valley floor landforms, river channels, coastal zones and patterns of terrestrial plant succession.

The examples of land-water ecotone management presented here were chosen to illustrate the integrated, self-organizing components of this valuable landscape feature. Increased understanding of landscape and ecological process has increased the number of management options currently available for the conservation and restoration of land-water ecotones. Further understanding of locally and regionally important ecological processes at these ecosystem boundaries, and identification of ecologically important features along river systems and coastlines will foster development of additional management options.

Defining economic values associated with improved environmental services and non-consumptive uses of riparian areas represents a challenge that may extend well beyond the present benefit-cost paradigm of natural resource economists. The development of informed environmental constituencies must precede the coordinated movement of hundreds of local, state or provincial, national, and international regulatory jurisdictions toward common environmental goals. Such progress in our way of doing things clearly depends on formulation of ecologically relevant natural resource and economic policies. This must be guided by ecosystem science that fosters regional understanding of ecosystem function. Success in this endeavour at the land-water ecotone may well constitute success in the broadest sense. Practical expertise of broad ecological relevance will be developed through successful ecotone management. Of perhaps more importance in many regions, land-water ecotones represent highly sensitive landscape units. Sustainable protection there will protect key processes and features on adjacent, less sensitive upland and aquatic habitats.

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