AQUATIC ENVIRONMENTS OF THE AMERICAS: BASIS FOR RATIONAL USE AND MANAGEMENT

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ABSTRACT

The Americas contain large population centers where surface waters are intensively managed or changed as a result of human activity. In addition, the Americas have vast undeveloped aquatic resources, use of which will proceed in parallel with population growth and economic growth. Given that the concept of ecosystem management now is widely accepted, it seems possible that the future use of surface waters can be accomplished in ways that preserve their broad utility far more effectively than has been typical in past decades. One challenge for ecosystem management is the great natural diversity of ecosystems. While regional variation cannot be overlooked, the water sciences have developed principles that apply across widely varying ecosystems. A rational basis for ecosystem management lies in the natural scope of environmental variation, which can be used in setting limits on anthropogenic change. The natural scope of variation reflects the range of adaptation for resident biotic communities, which in turn determine many of the economically significant characteristics of aquatic ecosystems. Management schemes that constrain variation of the managed system primarily within the natural scope of variation can be consistent with sustained value of the system for varied purposes, whereas management schemes that push environmental variation far outside the natural scope of variation often will produce unexpected costs that offset the intended benefits. The most important environmental variables to be considered in assessing the natural scope of variation include flow, morphometry of channels and basins, suspended load, dissolved solids, dissolved gases and introduction of new species.

INTRODUCTION

The Americas as a whole show an extraordinary variety of aquatic environments. In the arid portions of the American Great Basin or the Eastern side of the Southern Andes, for example, surface waters may be so saline that they are capable of supporting only specialized organisms having high tolerance for salt. At the same time, we find on the Canadian Shield and on the Brazilian and Guyana Shields of Latin America waters whose salt content is almost as low as that of rain (Figure 1). Where erosion is rapid, as it may be on the flanks of the Andes or in the semiarid plains of the United States, the rivers carry large loads of suspended sediment, whereas the rivers of forested flatlands, such as those of Rio Negro or southern tributaries of the Orinoco, carry only very small amounts of suspended solids. Aquatic environments of the Americas also span a vast range of conditions for temperature, nutrient supply, biotic diversity and all other environmental attributes.

In the face of natural variation that spans several orders of magnitude for numerous environmental attributes, we must ask whether it is feasible to create a general framework for the management and wise exploitation of aquatic ecosystems. Will the application of aquatic sciences be predominately regional, or do we find overriding principles that can be applied broadly?

The thesis of this presentation is that aquatic ecosystem science presently is in possession of sufficient knowledge to guide the use and development of aquatic resources. While regional variation is important, it should not obscure the utility of generalizations that have developed over the century and a half that inland waters have been studied.

SETTING LIMITS FOR ANTHROPOGENIC CHANGE

The Americas still have many undisturbed or minimally disturbed waters. Development of the landscape eventually will affect these waters either directly, as through impoundment or waste disposal, or indirectly, as through transport of combustion products through the atmosphere.

There has been for about 25 years now a strong tension in many nations between those who emphasize protection of the environment and those who point out that the use of natural resources is essential for human welfare. The notion of a balancing point involving use and exploitation has been generally accepted as a means of resolving this tension. Some environments of particular beauty or value will be protected entirely from exploitation, but the majority of environments will be used in some degree or another. At the same time, there seems to be a general consensus that exploitation of natural resources cannot be done for such narrow purposes as in the past, but rather must take into account all possible costs and benefits as part of an overall management plan. We have begun to call this "ecosystem management" (Christensen *et al.* 1996).

The scientific and technical challenge for ecosystem management is to find a compromise between use of a resource and protection of its continued integrity and productivity. We know that a species population, when exploited for human purposes, will show an optimum yield at a certain level of exploitation. Further efforts at exploitation are not only more expensive, but also result in lower yield (Figure 2). In essence, the principle of ecosystem management asks us to estimate the optimum yield not just for a species population, but for a cluster of environmental assets belonging to a given ecosystem or ecosystem type.

ADAPTIVE RANGE OF THE BIOTA AND THE SCOPE OF NATURAL VARIATION

Organisms respond to all human perturbations of the environment, and thus provide a basis for estimating degree of environmental change. The concept of indicator organisms or biotic indices, for example, is well recognized (e.g. Karr 1991). Our focus here, however, is not on the assessment of change that has already occurred, but rather on the forecasting of change in an environment that will be exploited or developed. In other words, how can the tolerances of aquatic communities be used in setting upper boundaries for human-induced change in aquatic ecosystems?

The answer to the problem of forecasting lies in the concept of adaptive range. In a given stream, lake, or wetland, the resident organisms are comprised of populations that are adapted to cope with the prevailing range of physical, chemical and biotic challenges; we can call this range the "scope of natural variation". Changes forcing the environment significantly outside the scope of natural variation will result in wholesale biotic changes, usually with consequences for the overall usefulness or aesthetic appeal of aquatic resources. The nutrient supply of a lake provides an example. Natural processes produce variation in the nutrient loading of lakes (Figure 3). Thus there is a natural scope of variation for nutrient loads and concentrations. Small environmental changes that raise the nutrient loading, but still remain for the most part within the scope of natural variation, are unlikely to cause major biotic changes. If the nutrient loads are brought well beyond the scope of natural variation, however, large biotic changes can be anticipated. For nutrients, changes will occur in the composition of aquatic communities typically from more desirable to less desirable forms, with accompanying aesthetic changes and reduction in the utility of the water for domestic consumption, recreation and support of fisheries.

CATEGORIES OF CHANGE IN AQUATIC ECOSYSTEMS

Most types of environmental change in aquatic ecosystems involve one of six environmental features: (1) flow; (2) configuration channels and basins; (3) suspended load; (4) dissolved solids; (5) dissolved gases, and (6) new species. The importance of these factors is confirmed by recent analysis of causes for decline of aquatic species in the US and elsewhere (e.g., Richter *et al.* 1997). The general consequences of change in each of these categories are known, although the specifics may vary from one location to another. The scope of natural variation, together with the six categories of variation, constitute a general framework that will support forecasts of change at any given location.

1. Flow: Change in the hydrograph

We find in most aquatic habitats a rise and fall in the amount of flow, i.e., in the hydrograph. In streams and rivers, this variation typically takes the form of high flow during a wet season and low flow during a dry season, plus irregular brief episodes of high discharge caused by storms (Figure 4). In wetlands, hydrographic variation often takes the form of alternating inundation and drying at the surface or expansion and contraction of wetland perimeter (Figure 5). In lakes, hydrographic variations are less obvious, but may also be important insofar as they are accompanied by seasonal shifts in the amount of water entering and leaving the lake.

Human development of water resources often changes hydrographs. The most obvious cause of change is the control of flow by dams, but other causes are also possible. Most dams confine the hydrograph for production of hydroelectricity or prevention of flooding.

Hydrographic changes may also be caused by water diversion, particularly in arid or semiarid climates. The result of diversions often is drastic depletion of flow. The hydrograph also may change when land use changes. For example, a forested watershed shows

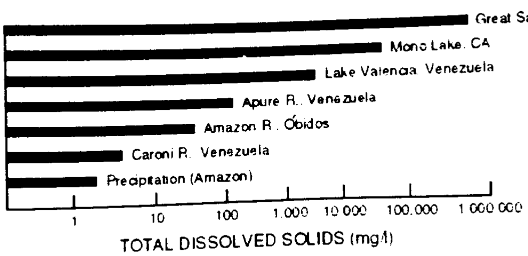

Figure 1. Natural variation in the total dissolved solids of surface waters in the Americas

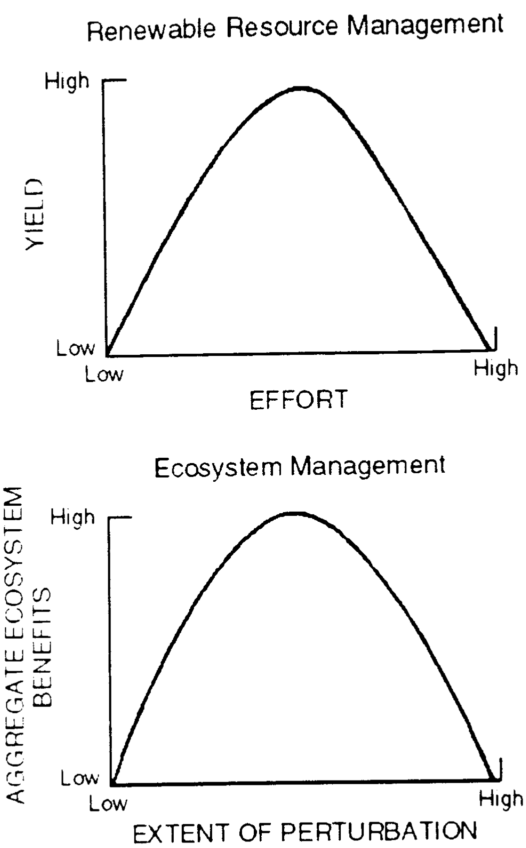

Figure 2. Illustration of the parallel between the yield curve for a single renewable resource and for aggregate ecosystem benefits

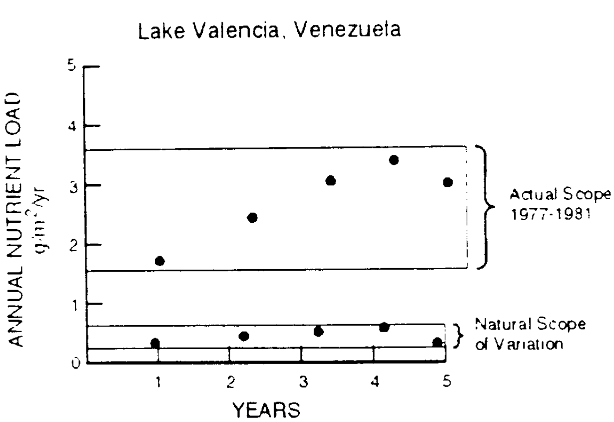

Figure 3. Scope of variation for nutrient supply in Valencia Lake, Venezuela. The actual scope of variation lies far outside the natural scope because of release of nutrientes to the lake from cities and industries

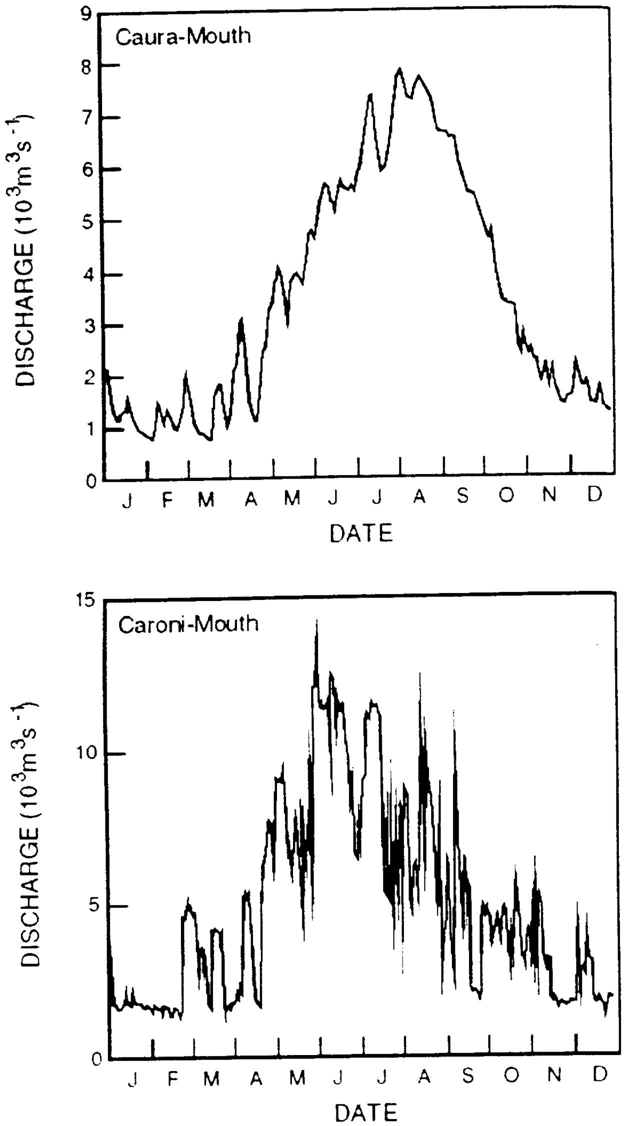

Figure 4. Hydrographs for the Caura and Caroni rivers (from Lewis *et al.* 1995). The Caura and Caroni rivers have very similar run off regimes, but the discharge of the Caroni is affected by the Guri Dam

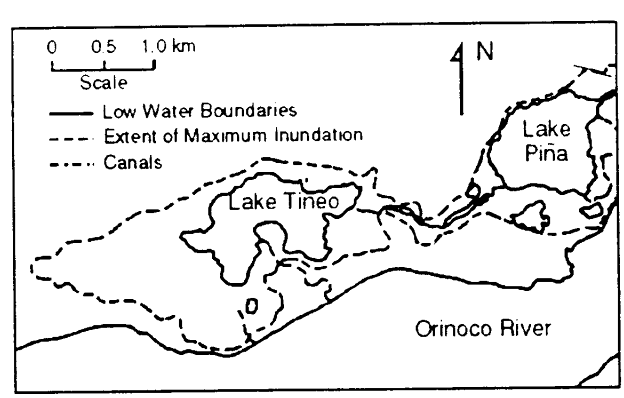

Figure 5. Effects of natural hydrographic variation on water level in riparian wetlands on the lower Orinoco River (Hamilton *et al.* 1990)

lower hydrographic extremes than a watershed that is deforested. While the exact forms of hydrographic disturbance vary from one location to another and from one form of development to another, the worldwide collective experience with hydrographic perturbation is very great. Effects can be organized around three aspects of the hydrograph: (1) storm pulses; (2) seasonal patterns, and (3) daily changes.

Storm pulses. Storm pulses play a large role in the transport of sediments, especially where the seasonal peak in the hydrograph is not very high. Movement of sediment is one means by which the physical complexity of stream and river channels is maintained, and reduces the annual accumulation of fine materials that might otherwise block the openings into coarse sediments such as sand, gravel, or cobble. Fishes, aquatic insects, and other kinds of organisms depend upon the presence of openings in coarse sediments for habitat space and for reproduction (Allan 1995).

Storm flow has other effects as well. For example, along the tributaries of the Orinoco River, brief storm events cause a rise in the stage of the river, which then flushes side channels containing phytoplankton and crustaceans (Figure 6). This flushing mechanism is responsible for more than 50% of the transport of suspended phytoplankton and zooplankton in the Orinoco River main stem. Suspended organisms maintain food webs in the Orinoco (Lewis *et al.* 1990). When the storm peaks change, the food web support may also change.

Seasonality. Hydrographic change may also involve the seasonal pattern of discharge. This type of manipulation can affect both the annual maximum and minimum discharges that would be characteristic of a stream or river. Hydrographs of rivers below dams typically involve suppression of the annual peak flow (Figure 7). Suppression of the annual peak reduces sediment transport and will affect wetlands and lakes that lie along rivers. These environments require rise in the water level for innundation. As the peak discharge is reduced in the interest of power production or flood control, the wetland and lake habitats are reduced in area and depth. Widespread biotic effects may include decline of fish production, change in the kinds and amounts of aquatic vegetation, occurrence of oxygen depletion leading to massive mortality of fishes and other organisms at low water, etc.

Changes in minimum flow may also affect aquatic habitats. For example, organisms adapted for migration or reproduction in the slowly flowing waters of a dry season may be unable to find proper conditions for reproduction and migration.

Changes in high and low discharges may also affect aquatic organisms through the disruption of communication between the environment and the organism. Organisms use the information in the rhythmic signal of the hydrograph to time reproduction or other life history stages (Figure 8). Suppression of the hydrograph signal thus has not only physical effects, but also behavioral effects on aquatic organisms.

Daily changes. Yet a third kind of hydrographic disruption that is common, especially for dams,

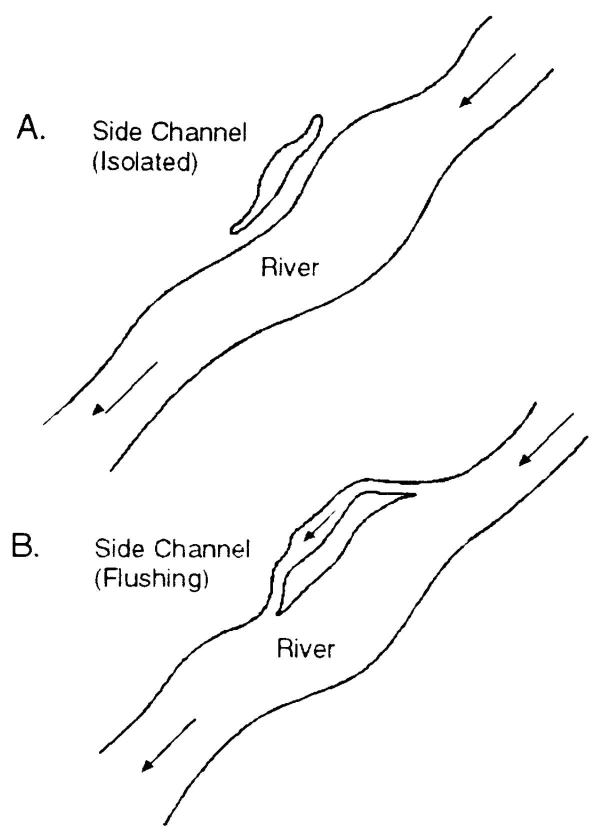

Figure 6. Illustration of the ecological role of short-term hydrographic variations caused by floods. Side channels build u planktonic biomass during isolation, and storm surges flush this biomass into the main channel

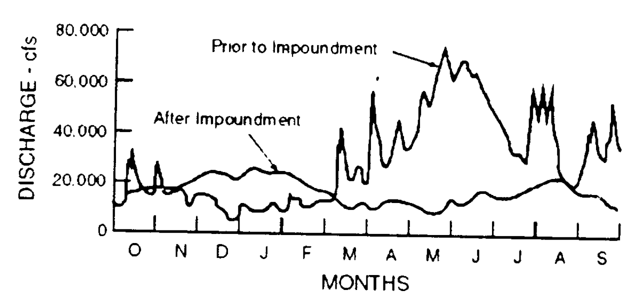

Figure 7. Illustration of a strongly regulated hydrograph (Colorado River below Glen Canyon Dam, Arizona. Source: Bureau of Reclamation)

involves daily change in discharge. It is efficient for a hydroelectric facility to operate on a demand basis. For dams that produce municipal electricity, this means a daily oscillation in discharge involving an increase in the early morning hours and a decrease at night when the demand for electricity is lower (Figure 9). Such 24 hour oscillation has no counterpart in nature, and some organisms are not well adapted to deal with it. For example, organisms may move into shallow water at peak discharge, only to be stranded in insufficient water as the oscillation rapidly carries the river discharge to a lower level (e.g., Lewis et al. 1995).

2. Reconfiguration of channels and basins

The United States has had perhaps the most extensive worldwide experience in the reconfiguration of natural channels and basins. This experience, some of which is now considered to have been poorly conceived, has involved the filling and drainage of wetlands, straightening of channels and confinement of flood plains. In many instances, short-term benefits have been smaller than anticipated and long-term costs have been surprisingly high.

The physical features of an aquatic environment are a component of habitat. The adaptive range of aquatic communities spans the range of habitats that are naturally available. Elimination or drastic reduction of these habitats thus moves the environment outside the adaptive range of many organisms. The result is change in living communities and in ecosystem properties. Parallel with these changes are undesirable direct and indirect effects on human interests, ranging from flooding to water-quality impairment, as natural ecosystem processes are disrupted physically.

3. Change of suspended load

All surface waters contain suspended material. Waters that have the lowest suspended load have weak sources of suspended material or lose suspended material rapidly because they are not moving. Waters that have the highest amounts of suspended material have rich sources and are moving sufficiently to keep it in suspension.

Human activity has a wide range of effects on the suspended loads of surface waters. Land use typically enhances the source strength of suspended material, which in turn raises the total suspended load of drainage networks. Because suspended load is transmitted downstream, land use in headwaters affects all running waters downstream. Running waters in turn bring increased suspended load to wetlands and lakes. Thus the magnification of sediment source strength in headwaters is in many senses similar to introduction of air pollution from a point source: the new load spreads broadly in the direction of flow.

Increase in sediment transport has a number of undesirable effects from the viewpoint of water resource management. High sediment load degrades the storage capacity of impoundments, reduces the value of water for domestic or industrial use and causes aesthetic impairment of waters. Consequences extend

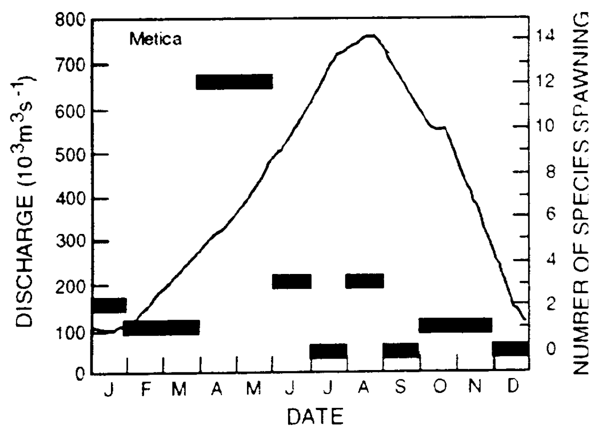

Figure 8. Illustration of the coincidence of specific hydrograph phases with reproduction of fishes (data from Galvis *et al.* 1989)

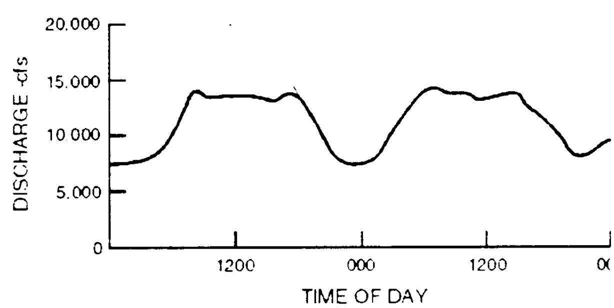

Figure 9. Illustration of 24-hour oscillations caused by the management of a dam for purposes of hydroelectric power generation (Colorado River below Glen Canyon Dam, Arizona)

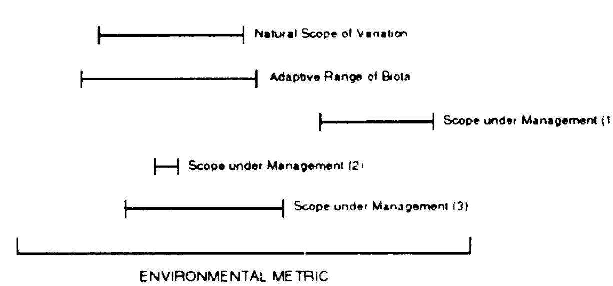

Figure 10. Illustration of the natural scope of variation, the adaptive range of the biota and the hypothetical scope of environmental variation under three different kinds of management schemes

well beyond these boundaries, however. Already mentioned is the adaptation of many kinds of aquatic organisms to the use of spaces within coarse substrates.

Where sediment load increases, the coarse substrates may be blanketed in such a way that they cannot be used, even if they are occasionally cleansed by high flow. In addition, suspended load affects the light environment, with consequences for photosynthesis and vision by aquatic organisms. Environments containing large amounts of suspended solids may remove virtually all light within a few centimeters of the surface. Under such circumstances, waters that support considerable photosynthesis on the bottom or the water column may be converted to waters that support no photosynthesis.

Waters of low suspended solids content typically are occupied by many kinds of organisms that use vision or more primitive forms of photoreception for purposes of orientation, feeding and reproduction. The addition of sediments to such aquatic environments drastically changes the conditions for life and often result in elimination or change of species composition. In the eastern U.S., sediment appears to be the most important factor leading to loss of species (Richter *et al.* 1997).

While human influence generally accentuates sediment transfer through land development or agricultural practice, human intervention in the water cycle in some cases reduces sediment transport, primarily by the impoundment of water. For example, the Glen Canyon Dam on the Colorado River changes the water from muddy to clear through the capture of sediment within Lake Powell (Blinn and Cole 1991). While the clear waters below the dam are perhaps aesthetically more pleasing, they are unnatural in this setting, and thus have produced a variety of physical and biotic changes. Waters deprived of sediment are highly erosive, because they only remove suspended material rather than adding some as well.

The result is reduction of streamside deposits such as beaches and sandbars, which are a source of aquatic habitat under natural conditions such as those that prevail in the Colorado River. In its natural state, the river would support virtually no growth of algae on the bottom because the bottom would be shifting sand and would be dark or almost dark because of the constant presence of sediment. Organisms would be adapted to life in the dark. Near the dam, however there now are dense growths of algae that were not present before, and visual predators prevail. Similar results are to be expected wherever turbid waters are replaced by clear ones.

4. Dissolved solids

Many compounds and elements contribute to the dissolved solids inventory of natural waters. For practical purposes, however, effects caused by perturbation of dissolved solids are most likely to occur through total ionic solids, labile organic matter, metallic toxins, and organic toxins.

Total dissolved solids. The total ionic solids content of water typically is magnified by agricultural use of water. This magnification is likely to be biotically significant only in semi-arid or arid zones. In general, a single agricultural use of water in a semi-arid zone will double the total ionic solids content of the water. Increase of dissolved solids beyond approximately 1000 mg/l reduces the usefulness of the water for domestic purposes or for further agricultural use. Increases beyond about 3000 mg/l cause notable changes in aquatic communities (Bayly and Williams 1973). Salination of water can be forecast with reasonable accuracy from water source and water use in a particular area.

Labile organic matter. Labile organic matter includes primarily municipal or industrial wastes that are rich in organic matter derived from sewage or industrial processes. The primary environmental challenge connected with labile organic matter is depletion of dissolved oxygen, which will be dealt with in the section below on dissolved gases.

Metallic toxins. Metallic toxins (mainly Cu, Zn, Pb, Cd and Hg, along with semimetallic elements Se and As) are added to water by mining, industrial processes and, to a lesser degree, domestic wastewater. Mining is the most damaging because the sources in this case may persist long after mining has ceased. Aquatic organisms are extremely sensitive to dissolved heavy metals. From the viewpoint of adaptation, we can understand this sensitivity in terms of the natural geochemistry of the earth. Concentrations of dissolved heavy metals similar to those released by mining are rare in nature. Consequently, aquatic organisms have not evolved defenses to the challenges of heavy metals. In other words, mining and industrial processes may move aquatic environments far beyond their natural scope of variation, thus causing large biotic changes. Food chain effects, and especially biomagnification, produce additional complications both for the living communities and for the human side of the food web.

Organic toxins. Organic toxins include primarily pesticides, herbicides and petroleum products. The fundamental difficulty here is that the natural aquatic environment does not contain these substances or contains them only in minuscule amounts. Consequently, the adaptive range of aquatic organisms is negligible and the essential degree of societal control over these substances is very high.

Nutrients. Nutrients present a very different sort of problem from metallic and organic toxins. The fundamental problem is one of biostimulation, and the substances in question are found consistently in the environment at biologically significant concentrations.

The biotic composition and productivity of a given aquatic ecosystem typically are controlled by the availability of either nitrogen or phosphorus, or the two of these in combination (OECD 1982).

Consequently, a large change in the concentrations or supply of these elements, particularly in their dissolved form, is likely to cause a change in community composition and a change in ecosystem properties. Experience shows that changes of this type are generally undesirable from the viewpoint of resource use.

The enrichment or eutrophication of surface waters is difficult to resolve because of the many ways in which human activity liberates nitrogen and phosphorus to inland waters. Major pathways of influence include land clearing, agriculture, municipal waste disposal and industrial waste disposal.

The scope of natural variation serves as a guide to the amounts of nutrient enrichment that might be consistent with an optimal resource management scheme. Nutrient concentrations and loads for given locations show substantial variation from year to year and season to season.

Increments of load within this range of variation may cause minor changes, but are less likely to cause the drastic changes that will occur if the loading is increased to such a point that it falls primarily outside the historic scope of environmental variation.

Because concentrations and loads of nutrients reaching inland waters vary greatly in nature, the allowable increments in loads and concentrations can also be expected to vary. For example, the degree of human control over nutrient release necessary in oligotrophic waters, such as those of the Brazilian Shield, Canadian Shield or many montane environments, is very high. In contrast, a degree of control over nutrients in nutrient-rich zones such as alluvial plains is not so great. Thus the scope of natural variation helps us decide the degree to which we must exercise control over nutrient release.

5. Dissolved gases

Of the numerous gases dissolved in water, the one of primary concern for management of aquatic ecosystems is oxygen. Although oxygen is absent from surface water under natural conditions in some cases, surface waters characteristically contain oxygen in sufficient amounts to support a wide variety of organisms. Some of the most drastic changes in aquatic environments occur with the depletion of oxygen, which is essential for the support most organisms other than microbes. Thus the conversion from a continuously oxic to a continuously or periodically anoxic situation is one of the most fundamental in aquatic ecosystems.

Human activity affects the oxygen balance of aquatic ecosystems both directly and indirectly. Direct effects primarily are related to the labile organic matter. As mentioned above, organic matter of this type comes in large quantities from municipal effluent and from industrial processes. Microbial use of oxygen in the decomposition of labile organic matter removes oxygen from the water more rapidly than it can be replenished by physical processes. This may result in drastic lowering or even elimination of oxygen.

Nutrient enrichment of water also may lead to oxygen depletion. Enrichment causes the accumulation of biomass, which may decompose periodically in a catastrophic way that demands most or all of the oxygen in the water, thus leading to mass mortality of fishes and other organisms.

Dissolved oxygen is a major issue for the management of inland waters. The scope of variation for oxygen concentration in most surface waters is relatively narrow, and the possibilities for perturbation of oxygen concentrations are high. This problem of oxygen management may be especially high in the tropics, where water holds less oxygen because of its warmth (Lewis 1996).

6. New species

The range of adaptation for a species population within an aquatic ecosystem includes interactions with all of the other organisms that are characteristically present in the community. In addition, species populations typically have some reserve capacity to deal with challenges from organisms that live within the same region and have been part of the evolutionary history of the species population. In contrast, the species population does not always have as part of its adaptive range mechanisms to deal with challenges from organisms that are exotic. It may happen that some of the generic defenses of the species population may allow it to compete with or persist in spite of the introduction of an exotic predator or competitor. In many cases, however, the introduction of exotic species leads to radical biotic change involving a new equilibrium among the species that make up the aquatic community (e.g., Minckley and Deacon 1991). Experience shows that the new equilibrium is seldom viewed by humans as beneficial.

CONCLUSION

The vast water resources of the Americas will come progressively under management and exploitation. Past errors in water resource management can be avoided by the application of basic principles from aquatic ecosystem science. Most important is the adoption of an ecosystem management framework that takes into account the full range of costs and benefits for aquatic ecosystem use (Figure 10). Limits of perturbation can be estimated initially from the natural scope of environmental variation. In general, perturbations that are held within the range of environmental natural variation will be consistent with effective ecosystem management, whereas perturbations outside this range will generally sacrifice narrowly defined gains for more broadly defined and potentially offsetting losses.

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