Restoring Damaged Aquatic Ecosystems

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> *The sobering prospect is that most of the major public decisions about resource use and environmental management will be made in the face of large uncertainty deriving from ignorance of physical and biological systems and from evolving techniques and social values.*
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> Gilbert White, 1980
> (*Environmental Science* 209:183-190)

> *We all live on this beautiful water planet which we have mistakenly chosen to call Earth.*
>
> Anonymous

Aquatic ecosystems must play a major role to ensure that water, which is both essential and scarce, is always available for both present and future generations. This has become even more urgent in light of the ongoing increase in total world population and predicted changes in the world climate. Since aquatic ecosystems have been damaged at a rate far in excess of both natural restoration and anthropogenic restoration, it is essential that both restorative processes be accelerated. However, ecological disequilibrium, evolutionary processes, and invasive species are likely to disrupt both processes. Most current debate focuses on water distribution; however, since the health of the aquatic ecosystem plays a major role in water quality and availability, it is argued that sustainable use of the planet requires that this attribute be given greater attention. The prospects for fully restoring damaged aquatic ecosystems to predisturbance conditions increasingly appear unlikely. Partial restoration now appears to be a more accurate description of the process, although full ecological restoration should always be an aspiration.

Key Words: Restoring aquatic ecosystems; Ecosystem restoration; Adaptive management; Unified strategy; Restoration trust fund.

Aquatic ecosystems are responsible for a wide variety of functions valuable to human society. They transform wastes to less objectionable, sometimes useful, materials; recycle nutrients; recharge groundwater aquifers; serve as habitat for wildlife; are a valuable recreational and aesthetic resource; attenuate floods; and augment and maintain stream flow. The world's rapid population growth, coupled with the industrialization of many parts of the world, has resulted in pollution of surface waters by insecticides, toxic chemicals, sewage, petroleum and petroleum products, eroded soils, and a variety of other stresses, including urban runoff from the creation of impervious surfaces such as roads and buildings. At the same time that these stresses have increased, water consumption has increased dramatically, as have interbasin transfers of water, damming streams, and the like. The increased delivery of sediments from agriculture, construction projects, and clearcutting and other forestry management practices in terrestrial systems has produced turbidity and sedimentation in riverine channels, lakes, and reservoirs, and concomitant losses of water storage and conveyance capacity. All these stresses have reduced both the quantity and quality of habitat for fish and wildlife, as well as damaged recreational and aesthetic values important to the tourist industry. These trends are accompanied by the extinction or endangering of aquatic organisms and reduce many beneficial water uses, including drinking, swimming, and fishing. Arresting these trends and restoring the self-maintaining, self-regulating capacity of aquatic ecosystems to some semblance of their former state are essential. Enlightened societies in various parts of the globe have already begun halting trends and restoring ecosystems and have provided both economic and ecological benefits in so doing.

Practically all aquatic ecosystems have been damaged (i.e., altered from their pristine condition) by anthropogenic activities. With the human population at its present size and distribution, restoration to pristine conditions may not only be ecologically improbable but could result in strong social resistance both because of

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financial drain and disruption of present human activities. Partial restoration does not imply such grand objectives but does suggest making most aquatic ecosystems more ecologically sound than they now are. This action would deter society from continuing to damage systems, which, in the minds of many, is the only course of action since ecosystems cannot be returned to their predisturbance condition. To another mindset, which takes as a *sine qua non* that continuing destruction is not acceptable and neither is the present condition, some improved condition is highly desirable. This ecologically improved condition is the context in which the word *restoration* is used. In earlier publications (e.g., Cairns et al., 1977), I used the word *recovery* to describe the improved state of ecosystems due to natural processes, although I was well aware at that time that the system did not recover to its predisturbance condition. However, self-maintenance is a very desirable goal, especially since all ecosystems are dynamic and change is normal.

The first badly damaged riverine system my colleagues and I examined in Virginia (Cairns et al., 1971, 1972) did recover to a remarkable degree (only mollusks failed to reach an approximation of their predisturbance condition). On the other hand, I have found since then that this experience in ecosystem recovery was exceptional — a large number of tributary streams provided colonizing species; the spill, although devastating, did not leave residual toxicants; the pH excursion was brief; and, finally, the area, except for the industry causing the spill, had very few other complicating anthropogenic discharges. Approximately two decades later, after many studies of and publications about the restoration of damaged ecosystems, the conclusion seems inevitable that restoration to predisturbance condition is a difficult, perhaps impossible, task (Cairns, 1989). One primary reason is that each ecosystem is the result of a *sequence* of climatic and biological events unlikely to be repeated precisely. A second compelling reason is that baseline information is inadequate on the predisturbance structural and functional attributes of the damaged system. For example, in the Prince William Sound Exxon *Valdez* oil spill, some data were available on the fisheries and the invertebrates, but the knowledge was not sufficiently detailed, structurally and particularly functionally, to provide a template against which restoration efficacy could be compared.

Bradshaw (1983) has called restoration the acid test for ecology. He believed that ecologists could construct ecosystems on paper in scholarly journals, but they have not yet shown that they can construct natural systems. In fact, restoration may have been ignored by mainstream ecology because it has the potential to show vividly the inadequacies of the underlying theory (Cairns, 1988). Despite the theoretical inadequacies of restoration, some examples illustrate what can be done with present technology and methodology, perhaps because nature itself is the best restorer of all. The tidal Thames River recovered from practically zero fish to over 100 species in approximately two decades (Gameson and Wheeler, 1977). A demonstration project on the Kissimmee River has shown that a channelized system can have its sinuosity restored and its hydrologic regime moved closer to its predisturbance condition, with a consequent ecological improvement of the damaged wetlands and other components of a riverine system (Toth, 1991). Numerous other cases of limnological system restoration are available (National Research Council, 1992).

The Urgency of Ecological Restoration

In Worldwatch Institute's 1990 State of the World Report, knowledgeable and reputable persons stated that the world has 40 years in which to achieve a sustainable relationship between human society and natural ecosystems. Nearly half this time is gone. The alternative — to continue the man-made serious depletion of ecological capital by a still growing population — will probably exceed the ability of Earth to sustain human society on a continuing basis. A substantial portion of the world's population is below the acceptable number of calories per capita, and another substantial portion survives on calories per capita that are not appreciably above the desirable level. For example, in a broadcast from Radio Beijing in October 1991, the average per capita calorie intake for the People's Republic of China was mentioned as now approaching 2600 calories. Of course, this, as a matter of choice for health reasons, may be good, because many overweight people consume calories far in excess of the desirable amount (e.g., Critser, 2003). However, for most of the world's people, this calorie amount is not a matter of choice, but a matter of necessity. The required caloric intake varies according to age, weight, and activities. Citizens of the United States average 3,732 calories per day, which is 50% more than low-income countries. Low-income countries consume less than 2,200 calories per day, and the United Nations sets caloric intake at 2,100 to sustain life, without allowing for work or play.

Any dramatic change in the agricultural delivery capabilities will cause vast suffering and, almost certainly, large numbers of deaths. As the pressure on ecological resources becomes more intense, the reserves, both ecological and societal, will diminish; events that might be tolerated under present circumstances will be disastrous. Today's students from kindergarten through universities will be the leaders of society in 2030 (the end of the 40-year time-period mentioned by the Worldwatch Institute). Will they have a strong sense of urgency to solve the problems that their elders are not yet aware of? Even today's limnologists engrossed with their specialized research probably do not have the strong sense of urgency that is necessary to mobilize society as a whole to cope with this problem. Politicians and other policy makers must be persuaded that time for mid-course correction is very short. Basically, the planet's population is growing at an unprecedented rate, and the ecological resources are being destroyed at an unprecedented rate. Clearly, neither of these trends can continue. Even if the Worldwatch Institute's predictions are off by 50 or 100 years, this time period is a tiny fraction of the time that the planet has functioned as a biosphere and is not even a large segment of the time *Homo sapiens* has been a recognizable entity. A stable quota of ecosystem services per capita with a growing population on a finite planet means that restoring damaged ecosystems is mandatory. Even if the population stabilizes and lost ecological capital is restored (e.g., old-growth forests), restoration of damaged ecosystems should continue to create a reserve of natural capital.

Adaptive Planning and Management

Most past efforts in environmental restoration have been based on a fixed goal and a prescriptive plan to achieve the goal. Since ecological restoration is a relatively new field and since almost every project has a substantial array of components different from other projects, scientists must learn by doing. Therefore, adaptive management, which recognizes the imperfect knowledge about restoration of complex, multivariate systems and which requires plans to be modified as new information develops, must be used. This new information may also alter social preferences. Thus, adaptive planning and management serves as a substitute for a decision-making process that is not based on trial, environmental monitoring, and error-correcting feedback loops.

Adaptation or modification depends on new information that suggests an alternative course of action as more productive. Therefore, an ecological monitoring system, consisting of biological, chemical, and physical components, is essential to ensure success of adaptive planning and management policy and programs. Monitoring will validate the assumptions that were correct and provide an error-control mechanism for those that were not. This approach means, of course, more than simply observing what is happening in a restoration project; a series of explicitly stated guide or trend lines with specific goals must be used at various stages. Attributes or characteristics of the system useful in ecosystem management will document success or failure with achieving these goals. Also essential is the initiation of decision-making when new evidence indicates an error has been made. Naturally, adaptive management will not succeed if the monitoring knowledge is not translated into modifications of the restoration policy and program design. Large-scale restoration projects requiring long periods of maintenance will not succeed without the support of a large component of the general public in that region.

Opportunity-Cost versus Benefit-Cost Analysis

The key to all policy decisions is a skillful evaluation of tradeoffs; in this case, not only between restoration and the present state of a damaged ecosystem but also between the various restoration alternatives: (1) restoration to a close approximation of predisturbance condition, (2) partial restoration, (3) construction of an alternative ecosystem, or (4) continuing the present situation. Yet another alternative is a mere stoppage of the accruing damage (which is not the same as “continuing the present situation” that is causing further damage). No existing decision-making protocol will establish, by itself, which of these choices to make, although the protocol can certainly help organize the information. One of the basic problems is that some attributes of restored ecosystems will have different ecological and social values. The policy decision will amount to choosing one set of values over another, although, of course, decision analysis and a variety of other methodologies can facilitate this process. As always, the weighting of values may be expressions of individual preference (the public choice approach for determining economic value) or expressions of collective preferences (social norms). For the cost-benefit analyst, individual preferences are measured in terms of monetary equivalence. One of the biggest problems with cost-benefit analysis is that it assumes a static view of human preferences. In contrast, the opportunity-cost approach means that the value of the restoration effort can be continually questioned by asking whether an action is providing the benefits originally described at the originally projected cost. If the effort is under providing resources necessary to meet the stated goals and objectives (as is often the case when the projected cost-benefit analysis is compared with the reality), the money may be better spent in some other restoration project or in some activity other than restoration for which the benefits appear to be greater. When the goal is to restore the health and integrity of a large complex ecosystem, all alternatives are worth exploring. Thus, advantage is always being taken of opportunities to derive the most benefit in the process rather than creating an inflexible system without decision-making feedback loops. Of course, the major difference between cost-benefit analysis and opportunity-cost analysis is that the latter is an ongoing process and, thus, is complex organizationally, whereas the cost-benefit analysis is not typically an ongoing process. A serious question exists as to whether any society can be collectively and adequately informed to make sound ongoing decisions of the type required by opportunity-cost analysis. On the other hand, the more inflexible system exacts a severe financial toll if the original estimates are misguided and no explicit decision-making process exists for correcting errors.

Responsibility for Restoration

Although the responsibility for restoration will be borne entirely or primarily by individuals, landscape-level restoration[2] and maintenance over a long period of time will frequently fall on institutions such as wood products companies holding large tracks of forest or, most likely, some level of government from the smallest regional component to the national, multi-national, or even international level. Because of the historic mission of various governmental agencies, regardless of level or even because of some recent events, the definition and goals of restoration (agencies use the term *restoration* in a variety of ways – e.g., National Research Council, 1992) may often vary widely from agency to agency. This discrepancy can obviously cause serious problems with no agreement on a unified definition of restoration. For example, in the United States, the Water Resources Development Act of 1986 and 1990 uses terms such as *environmental improvement* and *environmental enhancement*, as well as *restoration*, to describe new missions and authorities for the U.S. Army Corps of Engineers. Surprisingly, these terms are not adequately defined because they do not emphasize biological, physical, and chemical processes of aquatic ecosystems despite the fact that this emphasis was almost certainly the intent of the Water Resources Development Act. Astonishingly, the U.S. Army Corps of Engineers has associated restoration with fish and wildlife habitat enhancement rather than with hydrologic processes, although the latter are universally viewed as an area of expertise of the U.S. Army Corps of Engineers. The U.S. Clean Water Act of 1977 includes the physical restoration of aquatic ecosystems in its statement of objectives but fails to give the U.S. Environmental Protection Agency or any other agency the authority to develop a restoration program. In retrospect, it is not astonishing that discrepancies have occurred. If such events have happened in the United States, they could happen in other countries as well.

As another caveat, an explicit statement of goals should be agreed upon by all involved parties, since the way a goal is stated can direct policy and programs related to restoration. A good example of how the statement of a goal can direct policy and programs related to aquatic ecosystems is the no-net-loss of wetlands goal stated in the United States by the first President Bush and then included in legislation (U.S. Water Resources Development Act of 1990, P.L. 99-662).

Developing a Unified Strategy for Aquatic Ecosystem Restoration

The management responsibilities for the various components of an aquatic ecosystem — the lands, the waters, and the wetlands — are invariably fragmented among multiple governmental organizations and between the public and private sectors. This fragmentation is, of course, not usually a major obstacle for small-scale restoration projects, although even in those cases it may be. The various parties, both group and individual, with an interest in the way the decision is reached should have engaged in decision-analysis activities or something comparable so that negotiations result in socially sound decisions coupled with scientifically sound decisions. Regrettably, the history of river basin planning is more likely to demonstrate that efforts to establish central control over the programs of independently funded organizations have not worked, possibly because independent funding diminishes their incentive to cooperate. Invariably, the directives of a central organization, such as a river basin authority, are less compelling than the political allegiances, legislative mandates, and, most important of all, budgetary allocations. By first establishing common goals and explicit directives, conflict will be somewhat reduced among the various interest groups. In addition, however, among government agencies, failure to cooperate should diminish the cash flow. In short, a penalty should be assessed for resisting implementation of commonly negotiated goals and strategies. Inevitably, of course, organizational conflicts will arise, and specific arrangements should be developed for resolving such conflicts. Faculty in academic institutions should be charitable toward governmental failures in this regard because the same barriers exist to interdisciplinary activities on campuses. Furthermore, students are initiated into a discipline by a series of tribal rites in such a way that they are not encouraged to venture into professional relationships with those in other disciplines. The academic community must bear at least as much responsibility for failure to integrate science

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[2] Landscapes usually consist of a diverse array of ecosystem types (e.g., wetlands, forests, grassland) that collectively contribute to landscape-level interactions. Anthropogenic activities (e.g., roads, shopping malls, housing developments) create a fragmented landscape that is a mosaic (Forman, 1995a,b) of artifacts of human society and remnants of natural systems. Only when one examines ecological restoration from a landscape perspective does building ecological corridors that connect the fragments and permits some exchange of biota become a major goal. Ecological corridors may restore some of the attributes of large ecosystems, such as self-maintenance, that smaller, isolated ecological fragments no longer have. Self-maintaining ecosystems are less costly to manage than fragments that have lost this attribute because the fragments require more management (i.e., more subsidies). However, these corridors will displace or alter some human artifacts (e.g., highways), so skilled regional planning is essential to maximize benefits and reduce costs. For example, "greenways" also serve as wildlife corridors, but are also useful as nature trails. The wildlife corridors increase both resilience stability, the ability to recover rapidly from disturbance, and resistance stability, the ability of an ecosystem to resist disturbance (e.g., Tilman et al., 1996).

as the governmental agencies. Some uncharitable persons might feel that the academic institutions are more responsible since most persons staffing government agencies were educated in the academic system.

Restoration Trust Fund

Three compelling reasons indicate the value of establishing a restoration trust fund:

1. Many ecosystems have been damaged for long periods of time and by so many entities (many are no longer in existence) that obtaining significant funds from the perpetrators of the damage is unlikely. In this case, only society can be expected to pay the bill — since the society in which the damage occurred presumably permitted it through inaction or even, in some cases, may have condoned it.

2. An ecoaccident or accidental spill of hazardous materials, particularly during transportation, may frequently result in massive ecological damage. If the transporter is a large multinational corporation, funds may be readily available for restoration. However, in many cases, transportation is carried out by small organizations acting on behalf of the large multinational corporation, and the small organizations frequently have little or no financial reserves. The magnitude of this problem could be reduced by requiring all companies engaged in these activities to be bonded for such damage or to carry insurance policies as part of the cost of conducting this business. However, environmental activist groups in the United States have often insisted on an unlimited bond or insurance coverage, which commercial organizations are understandably unwilling to sell. As a consequence, this policy is most likely to succeed if finite financial limitations are placed on the bonding or insurance. This restriction requires that at least some restoration costs will be covered, but the costs will often exceed the amount of the insurance, and society must then pay the remainder.

3. Such organizations as the National Science Foundation in the United States and its counterparts worldwide do not have adequate research support for all the restoration activities that need to be carried out in the very near future. One approach to increasing this financial base is to include some research components in each and every project. The premise is that organizations creating environmental damage will be paying for some of the research costs for restoration of damaged ecosystems. On the other hand, carrying out research means high uncertainty, and industrial organizations particularly dislike dealing with uncertainty about costs. As a consequence, a trust fund should be available for those instances where the research effort does not achieve the goals and some alternative effort must be made. Industries are much more likely to carry out research in restoration and to try innovative techniques if they know that costs have a ceiling beyond which they are not responsible.

All nations should have such trust funds. However, even the wealthiest nations will not have adequate sums to cover all possible projects; therefore, priorities will have to be set. For the less wealthy nations, a global trust fund, probably administered by the United Nations, should be established so that projects in critical ecosystems can be carried out even though the country might require a subsidy for the project. The source of such funds is always a matter of concern. The easiest method to secure funds is to take them from general revenues. However, at the time this manuscript was being completed, the United States was suffering a massive budget deficit and would undoubtedly fiercely resist major allocations of funding for restoring damaged ecosystems. If one of the world's wealthiest nations is unlikely to provide such major funding, other nations are unlikely to do so as well, especially those countries whose per capita income is appreciably less. New taxes are never popular, but taxing the activities that are environmentally damaging might provide at least some funds.

Above all, the administration of these funds must not be left entirely to bureaucrats. Scientifically sound decisions should be capable of withstanding the peer-review process, and the establishment of such a process is essential to any undertaking that is not yet routine.

Local stewardship and initiatives for program planning and leadership should increase. As Rene Dubos said, "Think globally, act locally." Programs designed, led, and administered at the local level will be more critically scrutinized by knowledgeable people, and people receiving the benefits should be willing to pay for these programs while simultaneously seeing that the money is well spent. Despite some notable success in aquatic ecosystem restoration (e.g., National Research Council, 1992), large systems have not fared well. For example, the National Research Council (1992, p. 8) recommended that reaches of certain large rivers and their floodplains be designated as restoration templates and should be protected as quickly as possible. Over a decade later, this recommendation has not been implemented to the extent necessary to provide adequate templates. Without suitable templates, large-scale restoration becomes problematic.

Deleterious Societal Wastes

Restoring damaged aquatic ecosystems will be exceedingly difficult until the presence of toxic materials and other societal wastes is markedly reduced. In aquatic ecosystems, toxic substances are present in contaminated sediments, the water column, and in aquatic organisms themselves. Even at concentrations that are not fatal, such substances may impair normal function. Toxic substances in contaminated sediments may be released into the water column by changes in water chemistry and temperature or by activities of organisms that inhabit the sediments. Toxic substances in living materials can be bioconcentrated via the food chain; some chemicals act synergistically; and some are very persistent (Hoffman et al., 2003). A brief discussion follows of some of the difficulties with the present system and some alternatives to the present system. Present practices are not ideal for restoring damaged aquatic ecosystems.

As of May 1989, over 8 million chemicals were listed on the American Chemical Society computer registry of chemicals and slightly over 70,000 were recorded as in more or less daily use. The number of species on Earth is estimated to exceed 30 million (Wilson, 1988). The Toxic Substances Control Act passed by the U.S. Congress requires that "evidence shall be provided regarding the effects on human health and the environment for all new chemicals and all old chemicals used for a new purpose." This and other legislation in the United States puts the burden of proof regarding human health and environmental effects upon the organization proposing to either produce or utilize these chemicals to show that exposure to humans or natural ecosystems will result in no deleterious effects.

Considerable debate still exists over exactly what type of evidence should be provided. However, indications are clear that the probability of harm to human health and the environment from the proposed use should be documented. Unfortunately, industrial wastes dischargers, users of agricultural chemicals, etc., often claim no evidence of harm when, in fact, this statement may indicate ignorance about the problem rather than be a scientifically justifiable statement. Lack of evidence may result from failure to investigate effects in natural systems and/or failure to use definitive toxicity tests under controlled laboratory conditions. In the United States and Canada, the policy of presuming a citizen innocent until proved guilty is very well established, although at some times the fragility of this belief is evident. However, to apply the same concept of innocence until proved guilty to a chemical is absurd. All chemical substances have a deleterious effect at some concentration and time of exposure. This fact even applies to such necessary things to human well-being as vitamin A or fats. Evidence on the probability of harm is very important to the ecosystem restoration process.

Determining the threshold, concentrations, and conditions of exposure below which no-observable-biological-effects are noted and above which adverse effects are noted is a probabilistic exercise requiring scientific evidence. Since all chemical substances can be deleterious to either human health or the environment under certain conditions, a substantive evidence base must be generated before any statements of hazard or risk can be made that are scientifically justifiable. Therefore, the statement that "there is no evidence of adverse effects" should be replaced by "scientifically justifiable evidence indicates a low probability of harm to human health and the environment under the following conditions." The burden of proof should rightly fall on those organizations benefiting from the proposed use of a chemical rather than on society as a whole.

April 22, 2000, was the thirtieth anniversary of the first Earth Day celebration in the United States. In all Earth Day celebrations, a call is set forth for industries to stop discharging their wastes into the environment, particularly aquatic ecosystems. The reasoning is: if industries would put forth enough effort and commit more resources, wastewater could be treated so that it could be recycled through the plant and not discharged into natural systems. The materials recovered from the wastewater could be used in the manufacturing process or, when not possible, stored in drums. Of course, technology is not available in most cases to make this recycling possible and, in other cases, is regarded by industry as prohibitively expensive. Doubtless, the ecological restoration process will be less than perfect for some time to come.

However, if technology were available and the costs were within limits acceptable to industry, would this then mean zero environmental impact since, of course, no wastes would be discharged at the plant site? Removal of the last 5% of contaminants in very dilute situations, such as wastewater, costs many times more in energy, capital investment, and man hours of highly skilled personnel than removing the first 95% of the contaminants. The energy and construction materials for the additional treatment must be produced somewhere, which is unlikely to be done without having an environmental impact. For example, fossil fuels cannot be used for power generation without discharging carbon dioxide and other materials into the atmosphere, and the effects of greenhouse gases, acid rain, and the like are well documented. Nuclear power, of course, does not generate greenhouse gases or materials leading to acid rain, but does pose some other waste disposal problems that are also well documented. Obtaining materials for construction involves mining, lumbering, or some other comparable activities to obtain the raw materials, which are not without environmental impact. Refining the materials to a point of suitability for sophisticated waste treatment systems will definitely have some environmental impact because such activities cannot be totally contained.

As a consequence, zero discharge, even assuming it were technologically possible, would not result in zero environmental impact (although it might do so at a particular site). It would merely mean exporting the environmental problem to some other geographic area. Of course, the problem may well be exported, but the extent to which it is exported would not necessarily equal the problem that is being addressed. Clearly, redesigning wastes so that they benefit natural systems deserves more attention. This scenario is particularly applicable where greenhouse gases are created in the production of energy in attempting to eliminate a localized environmental impact at the cost of a global environmental impact. This holistic view of the process of waste treatment inevitably runs into a "Catch 22" situation. The only reason that the zero discharge concept persists is because society has a fragmented approach to problem-solving in controlling pollution. The idea of zero discharge is, of course, attractive to citizens near a manufacturing plant, and it is attractive to politicians for a variety of reasons; however, it does not bear close examination in the context of overall environmental impact reduction.

Since the first Earth Day, this zero discharge philosophy has resulted in waste (which could not legally be discharged into local ecosystems) passing from the producer of the waste to a subcontractor who supposedly disposes of the waste elsewhere. Some attempts to avoid meeting waste disposal requirements have made headlines, such as the famous garbage barge moving from port to port trying to unload its noxious waste that became increasingly more noxious as failure after failure to unload permitted the waste to get worse. Stories abound of trucks disposing of wastes illegally along highway roadside right-of-ways, etc. Stories about the avid interest of waste disposal subcontractors in bad weather (heavy rain, etc., that provides an opportunity for wastes to be discharged on the public highways in a way likely to escape detection) are too numerous not to have an element of truth in them. Often, the worst of these subcontractors file for bankruptcy periodically to avoid lawsuits. However, most of their illegal practices are undetected; once any waste gets into the transportation system, tracking it is much harder than if it is discharged from a fixed pipe from a particular industry. This example is merely another form of the zero discharge concept, namely, that wastes should not be introduced into the environment where they are produced but somewhere else out of sight. The result is almost certainly a greater global deterioration of the environment from these pollutants, since the disposal methods cannot be carefully monitored by regulatory agencies. This situation is not conducive to a successful restoration process.

Only a limited number of alternatives are open, but some appear far more attractive than the present system. A brief discussion of each follows.

1. Politicians and the general public must accept the idea that wastes should be dealt with where they are produced. If they cannot be effectively controlled at the site of production, production should cease or be reduced to a level at which wastes can be effectively reintroduced into the environment without producing deleterious human health or ecological effects. The benefits of this are that the environmental impact is associated directly with the production of whatever materials are being produced, and the monitoring of this impact is much easier than if the wastes are in the transportation system or exported to other areas of the world in some other way.

2. A waste minimization strategy is very attractive. In short, persistent, highly toxic wastes causing severe human health and/or environmental problems should not be produced; or, if they must be produced, the amount should be minimized through an examination of the production process. If an alternative production process results in less hazardous or less persistent waste materials, that process should be substituted for the one producing the more dangerous, persistent waste materials. If an alternative is not available at present, some method of reducing the amount of deleterious materials produced per unit of valuable materials must be carefully examined. Finally, if an impasse is reached, the materials should not be produced at all.

3. The public must accept that almost every societal activity involves some degree of risk to both human health and the environment and that the risks should be borne by the people who derive the primary benefits. This association of risks and benefits forces people to accept alternative ways of reducing environmental impact, such as recycling.

4. Recycling of materials that are deemed essential, but which cause a severe environmental problem, is the second priority following waste minimization. The benefits of recycling have been so eloquently and abundantly stated that further description of them here would be platitudinous. The problem becomes whether the political and social will exists to implement such recycling. This implementation can be

accomplished by reducing subsidies to producers of materials that can be recycled who are not presently doing so (e.g., the lumber industry pays only a fraction of the cost of producing timber in the United States) and by placing a penalty on individual households or industries generating large quantities of solid wastes.

5. The environment has a finite capacity to assimilate wastes, and a use charge for this purpose is not out of order. For example, power plants producing CO_2 should be required to rent a tropical rainforest or some other carbon sink for this purpose. Similar charges could be placed on automobiles through a gasoline tax. Portions of an aquatic ecosystem's assimilative capacity might even be sold to the highest bidder, but the contract should be only for a finite time, after which new bids would be accepted. These funds could be used to assure that the assimilative capacity is not diminished or exceeded.

Present waste disposal practices are unsuitable for long-term sustained environmental use. Global warming problems may directly affect agricultural productivity; enormous losses of top soil that far exceed the regeneration rate also affect agricultural productivity; and quality water is in exceedingly scarce supply, indicating that the hydrologic cycle is not being managed properly and groundwater aquifers are being depleted in excess of the recharge rate. All these and many other issues indicate that societal impacts on natural ecosystems must be substantially reduced or the ecosystems will no longer provide the services, such as carbon storage, that affect Earth's climate and serve as the human life support system.

The bottom line is that, unless a holistic view is taken of all environmental problems, including discharge of toxic wastes and greenhouse gases, and unless a more holistic strategy is developed for coping with them, the fragmented approach currently in vogue will produce an unmanageable situation in a relatively short time. I am optimistic about what can be done and pessimistic about what will be done.

The Responsibility of the Educational System

Implementing this restoration process will require resource management professionals skilled in integrated environmental management (Cairns and Crawford, 1991). Restoring damaged aquatic ecosystems without severely impairing industrial and agricultural activities will require an integrated, broad-based approach. Without doubt, professionals skilled in restoring aquatic ecosystems must have a transdisciplinary education, although specialization will still be necessary. Integrated environmental management is hard work, and professionals in this area will need the ability to coordinate activities that draw on a variety of disciplines (including hydraulic engineering, chemistry, aquatic ecology, fisheries, hydrology, ecology, fluvial geomorphology, social sciences, political sciences, waste treatment engineering, economics, decision analysis, and wildlife management, to mention a few). The same mix of disciplines will not be necessary on every restoration project, but no single discipline is capable of solving such complex problems without the assistance of other disciplines. For example, although many projects involving restoration of aquatic ecosystems are well intentioned, they have failed because hydrologic processes or the effect of adjacent terrestrial systems upon aquatic systems have not been adequately factored into the project design. Perhaps even more important is that large-scale projects will almost certainly not succeed unless the general public understands and supports them over long periods of time. Thus, a new emphasis on resource stewardship and ecosystem restoration cannot succeed without significant public understanding and support. The source of this understanding and support will be educational programs designed to raise the level of public knowledge and comprehension of the rationales, goals, priorities, and methods required for aquatic ecosystem restoration. The educational system has erected many barriers to the interaction of disciplines required for the restoration of complex multivariate systems such as aquatic ecosystems. Status and, perhaps, more important, promotion and tenure, are achieved by meeting the requirements of a specific discipline (which in itself is not a bad feature). What is harmful is that severe penalties may accrue to the academician for interacting with other disciplines, and, thus, integrated science and engineering may be sacrificed at the expense of disciplinary requirements. This tyranny of the disciplines that effectively blocks or severely restricts transdisciplinary activities in universities and colleges must be replaced with a greater tolerance of these activities, which ultimately will benefit the disciplines themselves. The quality control system represented by the disciplines must be maintained without permitting this quality control system to impair interactions among disciplines.

On the campus of Virginia Polytechnic Institute and State University, a Worldwatch Forum was active for many years. The Forum consisted of a 40- or 50-minute presentation by a person representing a particular discipline but addressing a problem that transcended a particular discipline. The Forum had several strengths:

1. The statements made by ecologists were challenged by economists and engineers and defended in a

way that not only met the requirements of the discipline but of the wider audience representing a variety of disciplines.

2. Since the Forum did not typically involve outside speakers but faculty members throughout the institution, the audience consisted in large part of speakers who had made a presentation. Members of the audience had typically attended over half the other Forums. In addition, students in a wide variety of disciplines had an opportunity to hear the revered paradigms of their own disciplines challenged by those in other disciplines.

3. No attempt was made to achieve a consensus, but each participant had the opportunity to see how other disciplines regarded one's individual discipline and to hear statements they might otherwise not hear. Every person sorted out his/her final beliefs. In order to permit students an opportunity to attend on a regular basis, methods were considered for giving class credit for attendance, and the Forum had the support of the president and provost, as well as of the Honors Program.

Concluding Statement

Global human population will probably continue to swell to at least 2050,[3] although conditions may then be appalling if no remedial measures have been taken. Since the aquatic resources on the planet are finite, restoring damaged aquatic ecosystems will be essential to maintain per capita amenities at, or close to, their present level. Of course, if dramatic climate changes such as are predicted by many forecasters occur, then the problems involved in restoration will be further increased. Concomitantly, present practices should be examined to determine if the use of water now appears as desirable as it did when the use was initiated. For example, should the surges from urban runoff during storms be routed into storm sewers that ultimately reach natural systems or should this water be put into storage systems that can be used to recharge groundwater, provide irrigation water for agriculture, or be used for a variety of other purposes? If runoff goes into storage, erosion and other damage to natural riverine and other aquatic systems could be decreased while simultaneously relieving the water shortage. The Thames River and other examples indicate that restoration is possible with present methodology and without sacrificing industry and municipalities. Further, restoration often has dramatic economic benefits. However, as in all cases of limited resources, decisions will not favor all equally. Therefore, only an informed public can make these important decisions and support them after they are made for long periods of time. This scenario is based on the assumption that political systems will be responsive to the wishes of an "informed public." A single Earth Day each year will not be adequate. The educational system must simply devote more time to explaining how the world works and how damaged parts can be restored.

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[3] Cohen (2005) notes that the human population in 2050 will be markedly influenced by human choices. The median projection of 9.1 billion is based on the assumption that fertility will continue its downward trend. If women had just one more child than assumed, the number would reach 10.6 billion. One-half child less would be 7.7 billion. If 2005 fertility rates remained constant, population would reach 11.7 billion.

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