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ECOSYSTEM MANAGEMENT AND THE CONSERVATION OF AQUATIC BIODIVERSITY AND ECOLOGICAL INTEGRITY[1]

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ABSTRACT: Ecologically effective ecosystem management will require the development of a robust logic, rationale, and framework for addressing the inherent limitations of scientific understanding. It must incorporate a strategy for avoiding irreversible or large-scale environmental mistakes that arise from social and political forces that tend to promote fragmented, uncritical, short-sighted, inflexible, and overly optimistic assessments of resource status, management capabilities, and the consequences of decisions and policies. Aquatic resources are vulnerable to the effects of human activities catchment-wide, and many of the landscape changes humans routinely induce cause irreversible damage (e.g., some species introductions, extinctions of ecotypes and species) or give rise to cumulative, long-term, large-scale biological and cultural consequences (e.g., accelerated erosion and sedimentation, deforestation, toxic contamination of sediments). In aquatic ecosystems, biotic impoverishment and environmental disruption caused by past management and natural events profoundly constrain the ability of future management to maintain biodiversity and restore historical ecosystem functions and values. To provide for rational, adaptive progress in ecosystem management and to reduce the risk of irreversible and unanticipated consequences, managers and scientists must identify catchments and aquatic networks where ecological integrity has been least damaged by prior management, and jointly develop means to ensure their protection as reservoirs of natural biodiversity, keystones for regional restoration, management models, monitoring benchmarks, and resources for ecological research.
(KEY TERMS: ecosystem management; ecological integrity; aquatic biodiversity; cumulative effects; conservation reserves; landscape planning; watershed analysis.)

INTRODUCTION

The majority of aquatic organisms have the unfortunate handicap of living downstream of humans, a basic fact only the most ideologically motivated can deny. As a consequence, the integrity and biodiversity of aquatic ecosystems is highly dependent on the way humans manage the landscape (Warren, 1979; Karr, 1991, Schlosser, 1991; Roth *et al.*, in press). Judging by pervasive and seemingly relentless declines in abundance and natural diversity of many monitored groups of aquatic biota throughout the world (e.g., Regier and Baskerville, 1986; Williams *et al.*, 1989; Nehlsen *et al.*, 1991; Allan and Flecker, 1993), we are doing poorly. Ecosystem management seemingly implies dramatic improvement in our performance as conservators of ecological integrity and biodiversity (Salwasser, 1992; Montgomery *et al.*, 1995), but until humans figure out what ecosystem management is and learn to implement it successfully for a significant period of years, how can we be confident it will protect and restore our aquatic biota and other water resources any better than past ways of environmental management?

Whether people are for or against it, almost everybody seems to have a different concept of what ecosystem management is. We think it is fruitless to argue about the conceptual and physical existence of ecosystems (e.g., Fitzsimmons, 1996), although it can be quite useful to argue about how to most usefully define their structure and boundaries (e.g., Jensen *et al.*, 1996) and about how they should be managed. Like it or not, the concept of ecosystem management isn't going to go away anytime soon, because something like it is necessary to address the vast natural and cultural wreckage of exploitation-focused, single-resource approaches to resource management that has accompanied European colonization of the globe. There should be little doubt that the struggle to define what ecosystem management is, and how or whether it should be implemented on the landscape, will be critical to the future of aquatic biota and other

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diminishing water resources. In this paper we argue that the approaches to ecosystem management proposed to date by government and industry fall far short of ensuring that future management will halt or reverse the deterioration of aquatic ecosystems.

In the rush of government agencies to re-define (or, more skeptically, re-package) their environmental management programs as ecosystem-friendly endeavors, they have failed to acknowledge that human cultures have throughout their history deemed their own "state-of-the-art" environmental management practices to be good and proper. At any given moment in history, there are always people who tout contemporary management practices as the Panglossian pinnacle of social and technological refinement, while the less zealous accept such practices as clearly improved and unquestionably sufficient to maintain desired resource conditions (i.e., ecosystem functions). Because our generation believes past generations of managers were wrong in such assumptions, we have now invented the term ecosystem management to connote a new and smarter approach. But what makes us so sure we've got it right this time (Stanley, 1995)? And what if we don't?

We have heard some scientists and managers claim that now that we have ecosystem management, whatever exactly it may be, we can proceed with large-scale development of the landscape for human purposes without fear of ecological retribution. Others, including many of those recently promoting the so-called "forest health" agenda in the United States, seem convinced that because ecosystem management implicitly incorporates rehabilitation of ecosystems, we must get on with it urgently to correct our past mistakes – we have to re-do management right, and right now, everywhere. More modestly, others suggest that the concept of ecosystem management at least opens the door for effective integration of scientific knowledge into management decisions (Montgomery *et al.*, 1995).

However, within the past century or so, rational people have advanced remarkably similar arguments and claims for soil conservation, clear-cut logging, dams, hatchery fish culture, irrigated agriculture, maximum sustained yield, multiple use, water quality standards, land grant universities, and forest planning, to name a few once-new concepts. Obviously the availability and widespread application of these technologies, arrangements, and institutions did not spare us the consequences of aquatic resource degradation. Each may have in its own way slowed or ameliorated some of the most egregious contemporary examples of environmental destruction (some have fostered more than their share of damaging side effects), but none has resulted in truly sustainable resource use or maintained ecological integrity (Regier and Baskerville, 1986; Soulé, 1991; Karr, 1991; Ludwig *et al.*, 1993).

In the following discussion, we examine several commonly proposed approaches to ecosystem management and discuss some of their crucial technical and operational shortcomings from the standpoint of conservation of aquatic ecological integrity and biological values. Then we describe an alternative strategy based on establishment of watershed-based conservation reserves that could potentially reduce many of the threats to aquatic ecosystems posed by uncertainty (and its evil step-sisters, ignorance and hubris) in ecosystem management. If we truly aspire to the goals of ecosystem management, we argue (butchering a time-honored proverb) that a watershed in the bush can be worth two in the hand.

THE RANGE OF NATURAL VARIABILITY

One of the most common precepts invoked to guide ecosystem management is the notion that human actions should either maintain or return ecosystems to within their range of natural or historic variability (e.g., FEMAT, 1993; Montgomery *et al.*, 1995). Although this concept does helpfully point toward viewing the past as the key to future management, we share the concern of Rhodes *et al.* (1994) that it has several major operational and practical limitations. This concept fails to weigh many of the most fundamental environmental realities that constrain ecosystem management, either in the technical or policy sense.

Is the *range* of variability in ecosystems conditions really what we seek to emulate, or is it more important to maintain in a broader sense the full pattern of states and successional trajectories (Frissell *et al.*, in press)? Strictly speaking, the range of variability is defined by extreme states that have occurred due to climatic or geologic events over long time spans. Nothing says these extreme states were favorable for water quality or aquatic biodiversity, and in fact such natural-historical extremes were probably no more favorable for these values than present-day extremes. From the point of view of many aquatic species, the range of natural variability at any one site would doubtless include local extirpation. At the scale of a large river basin, management could remain well within such natural extremes and we would still face severe degradation of natural resources and possible extinction of species (Rhodes *et al.*, 1994). The missing element in this concept is the landscape-scale *pattern* of occurrence of extreme conditions, and patterns over space and time of recovery from such stressed states. How long did ecosystems spend in extreme states vs.

intermediate or mean states? Were extremes chronologically correlated among adjacent basins, or did asynchrony of landscape disturbances provide for large-scale refugia for persistence and recolonization of native species? These are critical questions that are not well addressed under the concept of range of natural variability as it has been framed to date by managers.

We suspect that in most aquatic ecosystems, extreme states continue to be determined largely by high-magnitude natural events, whereas most human activities predominantly influence ongoing frequent and lower-magnitude processes, although at cumulatively vast spatial scales (Frissell *et al.*, 1986; Roth *et al.* , in press). Repeated, chronic, persistent, or anomalously extensive but sometimes subtle alteration of the pattern of lower-magnitude processes, such as the seasonal and diurnal patterns of river discharge, temperature, and sediment mobility, can have more severe effects on the integrity and resilience of aquatic ecosystems and biota than large floods and other single-pulse, catastrophic events of much higher magnitude (Yount and Niemi, 1990). Humans, however, are more likely to detect, perceive, and emphasize the latter category of catastrophic events as disturbances that exceed the known range of natural-historical conditions. The consequence is that the vast array of human activities that cause subtle but creeping and pervasive effects is de-emphasized or ignored by managers and regulators, and most planning and protection measures focus primarily on human activities known to directly trigger massive, unprecedented events of episodic proportions (e.g., massive industrial discharges, or collapse of a mine drainage retention structure). No environmental impact statement we have seen in the Pacific Northwest has evaluated (or otherwise disclosed) the chronic, cumulative effects of human activities that can cause small increases in the rate of local extirpation of breeding groups and simultaneous decreases in the rate of recolonization, which coupled can clearly produce strikingly rapid declines in species with population ecology typical of that in Pacific salmon (Frissell, 1993a) and many other formerly abundant aquatic organisms.

The concept of range of natural variability also suffers from its failure to provide defensible criteria about which factors' ranges should be measured. Proponents of the concept assume that a finite set of variables can be used to define the range of ecosystem behaviors, when ecological science strongly indicates many diverse factors can control and limit biota and natural resource productivity, often in complex, interacting, surprising, and species-specific and time-variant ways. Any simple index for measuring the range of variation will likely exclude some physical and biotic dimensions important for the maintenance of ecological integrity and native species diversity.

To further complicate things, many of the disturbance events that dramatically shape terrestrial systems (e.g., fire, windstorms) may have relatively subdued effects in aquatic ecosystems, whereas aquatic systems respond more dramatically to processes such as floods and acceleration of erosion that may have rather subtle or spatially restricted expression in the terrestrial environment. Such complications in the coupling of terrestrial and aquatic environments mean that extrapolating from one to the other is problematic and fraught with uncertainty. Each may be driven by different disturbance processes, even while linkages such as erosion and sedimentation, downstream flow of contaminants, and exchange between surface and ground waters connect the two systems inseparably. Therefore, perceived management problems in terrestrial systems, such as the depletion of older, larger trees, and proliferation of dense younger stands in some western forests that has recently been labeled a "forest health crisis," do not necessarily correspond to the major threats to aquatic systems. Indeed, in the forest health example, many of the proposed cures (e.g., salvage logging and massive thinning programs, continuing existing livestock grazing policies) pose far greater threats to fish populations and aquatic ecosystem integrity than do fires and other natural events that might (or might not) be associated with the "undesired" changes in forest structure (Henjum *et al.*, 1994; Rhodes *et al.*, 1994). For aquatic systems in the west, the management crisis arises from the cumulative and persistent effects of thousands of miles of roads, thousands of dams, and a century of logging, grazing, mining, cropland farming, channelization, and irrigation diversion (Frissell, 1993a; Wissmar *et al.*, 1994; Rhodes *et al.*, 1994).

Finally, for many kinds of ecosystems (e.g., low-elevation alluvial fans in the Great Basin, forested floodplain rivers of New England and the midwest, the cedar forests of Florida, grasslands of the Great Plains and Columbia Plateau), we have few or no unaltered representative sites and sparse historical records to reconstruct what natural-historical conditions looked like and how they were maintained. These ecosystems have been so starkly and extensively modified (and so sparsely studied, relative to their scale) that we cannot presently determine how they varied over time and space before destruction of aboriginal cultures and colonization by European man.

MIMICKING NATURAL DISTURBANCE REGIMES: THE GHOSTS OF IMPACTS PAST AND FUTURE

Another frequently cited guiding principle for ecosystem management is the notion that human actions should attempt to mimic natural or historical disturbance regimes (thus presumably remaining within the natural range of variation) (e.g., FEMAT, 1993). Even on its face, this concept faces logical trouble as a rationale for management. If natural disturbance regimes are the best way to maintain or restore desired ecosystem values, then it seems nature should be able to accomplish this task very well without human intervention. It is difficult to imagine how programming of additional artificial disturbances, such as more road construction and logging, can be necessary to return an ecosystem to its natural disturbance regime or to somehow improve or optimize that ecosystem's operation. The principle exception might be where a human intervention, creating a relatively small disturbance, is necessary to undo a prior alteration that otherwise would persistently impact the ecosystem – such as the removal of a dam, or an unstable road network. Strictly speaking, under this principle the sole task of management should be the reversal of artificial legacies to allow restoration of natural, self-sustaining ecosystem processes.

In actual application, this principle is not so strictly applied. It becomes a credo for shaping management actions such that they more nearly resemble the quality, spatial distribution, and temporal pattern of natural disturbance processes. But in this sense, the concept is haunted by at least two very consequential problems. Due to their shadowy, nearly phantom-like nature, we caricature these problems as ghosts that haunt the concept of ecosystem management.

Most ecosystem management plans that embrace the natural disturbance regime concept assume that we can simply start managing this way today, and all our management problems should vanish. The legacy of past disturbances, both natural and human, is tacitly denied. However, it is imperative to account for specific historical events, and their long-term legacies, in any attempt to consider how far an ecosystem has deviated from its natural-historical disturbance regime and what actions may be necessary to return it to some semblance of its former domain of behavior. A simple example is the case of aggradation of coarse sediments in streams following extensive human disturbance of their catchments. The effects of increased sediment yield on channel morphology and stability can persist for many decades (perhaps centuries) after the causal disturbance of the slopes of the catchment (Hagans *et al.*, 1986; Ziemer *et al.*, 1991). Large-scale natural disturbances, such as major landslides, can have similar effects. The result is that the impacts of future disturbances are contingent on the legacy of past disturbances – the Ghost of Impacts Past. The same magnitude or pattern of disturbance may have dramatically different effects in a catchment that has experienced such prior disturbances than in an identical catchment that has not had such a history. The Ghost of Impacts Past determines the response of an ecosystem to any particular disturbance regime, even though its presence isn't always obvious. If you don't believe this ghost exists, we are certain you will not see it. You will nevertheless suffer its consequences, and you will be left (as have many in the past) without a defensible explanation for why your management objectives were not achieved.

Presently, however, planning for ecosystem management remains largely focused on defining how and where traditional resource extraction activities and environmental disruption can be continued without irreversible net harm to water quality, biodiversity, and other ecosystem values (Frissell *et al.*, 1992; Grumbine, 1994). This emphasis presumes there exists some ecological space in which such disruptive activities can be pursued with no consequential ill effects. It assumes that we have the capability to identify such "free space" and to implement activities that will not violate it. It assumes (without checking) that watershed ecosystems retain inherent resilience that allows them to recover from continued human disturbances (Frissell, 1993b; Rhodes *et al.*, 1994). However, because of the persistence of many kinds of impacts in aquatic systems and because of the extensive nature of human activities in most catchments, any inherent ecological resilience or resistance these aquatic ecosystems may once have had is likely compromised by the Ghost of Impacts Past. Ecosystem management must be more than the search for the last free lunch. For watersheds and aquatic ecosystems, we have ample evidence that if there ever was a free lunch, we already ate it.

Even more problematic is the Ghost of Impacts Future. Natural disturbance events, both small and large, will continue, by definition in an unmanaged and unpredictable fashion. We think of these events as "wild disturbances," in the same sense that naturally produced fish are wild fish. Their behavior is not under human control and cannot always be anticipated. That is their nature. Even if the probability of occurrence, magnitude, and effects of such events can be predicted, their timing cannot be. The result is that even the best-laid management programs based on disturbance regimes can go badly awry. In fact, the more meticulously a management program is designed around a particular expected or desired disturbance regime and sequence of actions, the more likely it is to fail because of unanticipated natural events. The Ghost of Impacts Future prevents us from controlling disturbance regimes, and it is little more than hubris to assume that we manage disturbance regimes in the sense that they can be programmed and optimized for specific objectives. While humans can and do influence disturbance regimes (often in unanticipated ways), it seems to us disturbance regimes ultimately manage themselves.

WATERSHED ANALYSIS AND MANAGEMENT

Another important component of ecosystem management is watershed analysis (FEMAT, 1993; Montgomery *et al.*, 1995) and related methods that attempt to evaluate and eventually prescribe management actions based on cause-effect analysis and simulation models. Watershed analysis is a set of technical tools that, unfettered by bureaucratic encumberments, holds promise for assisting in the retrospective analysis of catchment change and aquatic ecosystem response. In this sense, it can be a way of getting a fix on the Ghost of Impacts Past and reducing the likelihood of management failure from this cause. But there are some serious limitations to what we can expect to achieve from watershed analysis, and we are concerned it is increasingly being oversold as a panacea for an accumulating burden of management problems that are as much political, ideological, and administrative in origin as scientific and technical, if not more so.

Although properly focused scientific analysis might help clarify the inadequacy of management premises and the causes of management failure (Underwood, 1995), watershed analysis as it presently exists (e.g., as portrayed in FEMAT, 1993, and subsequent federal documents) is not designed to accomplish this task. In fact, perhaps the principle flaw of watershed analysis as a management tool is that it does not provide a clear vehicle or protocol to link technical analysis and policies and decisions. The arguments of Montgomery *et al.* (1995) suffer from what we would characterize as an overly optimistic assumption that better technical analysis will in some unspecified way lead to better management plans, decisions, and outcomes. While agreement on scientific facts may help reduce some of the uncertainty and illusion in management, this view denies the overriding importance of ideological, philosophical, and political perspective in management. Facts gain their meaning through the lens of theory and world views (C. E. Warren, unpublished manuscript, Department of Fisheries and Wildlife, Oregon State University, Corvallis), and better data are unlikely to change world views – at least not for most people, and not very rapidly. Data, for instance, on the mechanics of debris flows in headwater channels have little intrinsic meaning or obvious relevance to most engineers, farmers, or silviculturists. The tragic risk is that by promising a technical solution to environmental problems, watershed analysis will provide an excuse that allows managers to avoid facing the full array of political, philosophical, and administrative dimensions of management reform. The mantra of managers will remain, "Let the scientists take care of it."

Perhaps more importantly, better scientific data may not unambiguously point the way for an honestly repentant manager either. Fundamental uncertainties, the Ghost of Impacts Future among them, will remain. In fact, after a really good watershed analysis, critical uncertainties will probably appear to the alert decision maker to loom larger than they ever have before, simply because the complexities of ecology and history will be a little less blurred by the lens of ideology. When was the last time science or new technology simplified your life? It happens now and then, but the opposite seems much more the rule.

As McNab (1983) pointed out to wildlife managers and scientists, one fundamental problem is that natural resource managers tend to resist close working relationships with researchers. Managers feel more comfortable in the political arena when they portray the ecological assumptions underlying their programs as proven facts rather than as tentative hypotheses. Good scientists are inherently skeptical and therefore often seem more a nuisance than a help to managers. To acknowledge uncertainty in the principles guiding a management program is to accept that failure or success of the program is itself a test of the underlying ecological assumptions. This requires managers and scientists to work together to establish and monitor criteria for evaluation, which in most cases will require explicit experimental designs incorporating unmanipulated control systems (McNab, 1983; McAllister and Peterman, 1992). Unfortunately, unexpected results can embarrass managers, especially the more intrepid or audacious ("ecosystem") managers who tend to take the lead in the development of new programs. Unless the largely uncertain and experimental basis of all ecosystem management programs is squarely faced, watershed analysis and similar assessment procedures conducted by researchers are unlikely to themselves markedly change or improve management. Only the most egregious mistakes of past management will be exposed, and the virtually uniform response of managers to retrospective analysis is that the lessons of the past are largely irrelevant because "We don't do that anymore" (they point out that now we use Best Management Practices, or buffer strips, or standards guaranteed to produce sediment-free roads, or some other change in management style they presume to lessen environmental impact).

Another serious problem with watershed analysis is that many of the necessary scientific tools for relating changes in physical systems to biological responses are weak or nonexistent. On the research side, some proponents of watershed analysis perpetuate the illusion that models or simple relationships exist that allow prediction of changes in particular fish populations based on changes in its physical habitat. In fact such capabilities are crude, and may in the best circumstances extend only to the general population trend or time to extinction that might be likely with a given physical scenario and good biological information on current population status (Rieman *et al.*, 1993). Existing models do a relatively poor job of predicting the general range of fish biomass likely under a given set of physical conditions (Fausch *et al.*, 1988; Hall, 1988), let alone the far more delicate task of predicting the abundance or harvest of individual species and populations (e.g., Hecky *et al.*, 1984). And we have even less experience with other kinds of organisms. General indices of ecological integrity, developed for multi-species assemblages of aquatic organisms or for habitat factors in specific geographic areas, do often have predictable correlative relationships with environmental stressors at least at coarser scales (e.g., Karr, 1991; Roth *et al.*, in press), but because the underlying causal mechanisms of these relationships are not fully understood, many managers and some scientists continue to reject them.

THE ECOLOGICAL AND SPATIAL CONTEXT OF WATERSHED CHANGE AND BIOTIC RESPONSES

The lack of success in mechanistically linking biological response models to physical driving models stems at least partly from a failure to pay appropriate attention to the geographical and ecological context in which models are derived and applied. This means not only that biological responses are likely to be regionally and locally variable depending on habitat conditions but also that the response in a specific habitat unit may strongly depend on its spatial relationship to other habitat patches in the ecosystem (Sheldon, 1988; Schlosser, 1991). For example, historical responses of fish populations and other biota may not reliably reflect future responses because the larger-scale context or habitat and metapopulation mosaic at the catchment level is changing (Figure 1).

This difference in biogeographic context creates profound implications for ecosystem management and the conservation of aquatic biodiversity (Zwick, 1992; Frissell, 1993b; Doppelt *et al.*, 1993). Unstated assumptions of past approaches to modeling and management of biological populations in aquatic ecosystems include the following: (1) disturbances are isolated and independent in their effects, and the ecosystem as a whole remains functionally intact; (2) biotic recovery at each disturbed site proceeds independently and relatively rapidly, also independent of the site's context in the ecosystem; (3) a steady, virtually unlimited supply of organisms is available to colonize disturbed habitat patches as they recover physically; and (4) biota and riverine habitats are largely homogeneous in distribution so that habitat and fish populations are readily replaceable, generic techniques of habitat modification are widely applicable, and the risk of failure or unintended side effects of management actions is minimal (Frissell, 1993b). These assumptions may be at least partly valid in a landscape that is relatively free of recent, large-scale human alteration or catastrophic natural disturbance (Figure 1a).

However, in a landscape that has been highly altered in a relatively short period of time, much different biogeographic dynamics may prevail (Frissell, 1993b). In this context, an aquatic habitat mosaic that is inherently heterogeneous becomes more highly fragmented and, from the standpoint of sensitive species, more patchy (Figure 1b). Most present production, abundance, and diversity of sensitive biota may be supported by the small proportion of the overall habitat mosaic that remains relatively undisrupted. Fragmented and isolated populations suffer elevated vulnerability to extinction through further habitat alteration or demographic or genetically-mediated reproductive failure (Zwick, 1992; Rieman *et al.*, 1993; Bradford *et al.*, 1993). The present distribution and life history patterns of such populations, largely governed by the availability of habitat refugia and the specific historical pattern of habitat alteration, determine their ability to respond to future changes in habitat. Biological responses are thus historically and spatially constrained, determined by the proximity and preadaptation of potential colonists for local conditions, the sequence of events and conditions that has occurred in key patches, and the specific local vagaries of juxtaposition of habitat patch types (Schlosser, 1991). Biotic recovery in such circumstances may lag far behind apparent physical recovery of local habitat patches (Zwick, 1992; Frissell 1993b; Doppelt *et al.*, 1993). As a result, many apparently suitable habitat patches across the landscape will remain unoccupied, leading the biologically naive

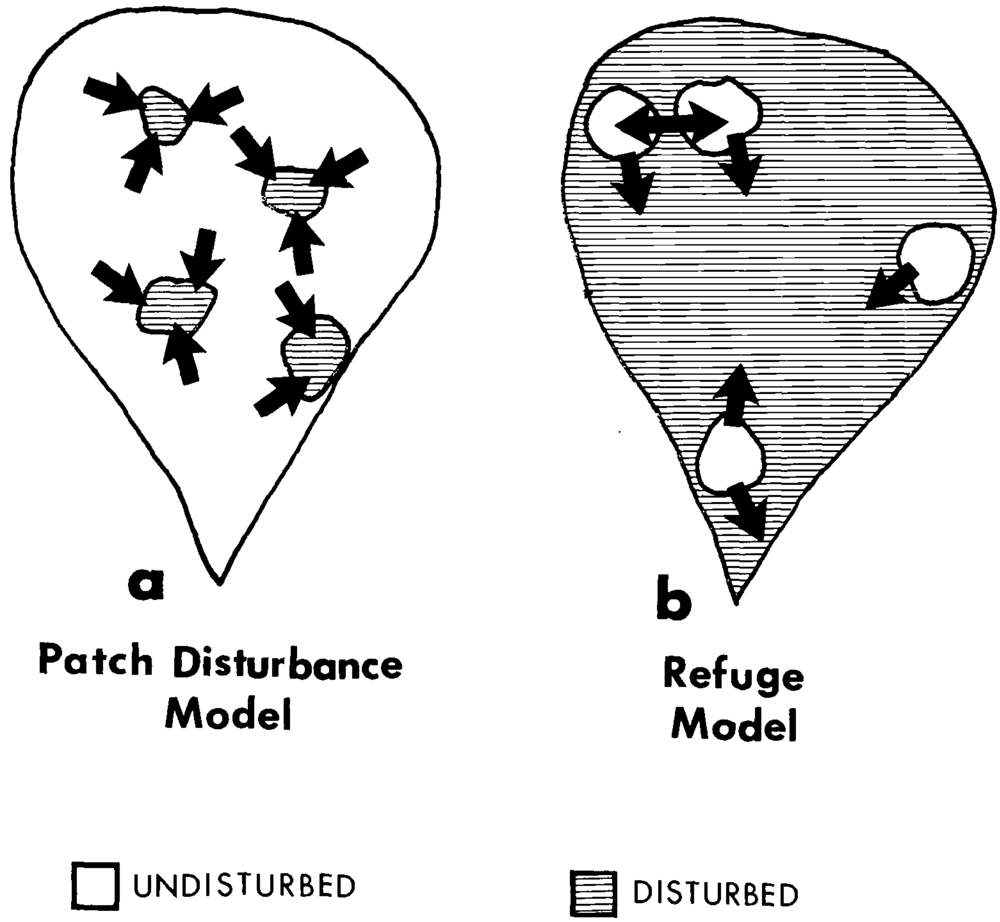

Figure 1. The Changing Biogeographic Context of Aquatic Ecosystem Management. In catchment a, degraded aquatic habitats (shaded) constitute isolated patches within a matrix of high-quality, richly-inhabited areas. Abundant, well-connected populations supply a steady supply of colonists (arrows represent colonization vectors) to re-establish populations in disturbed areas. In catchment b, high-quality habitats are isolated remnants in a matrix of disturbed and degraded habitat. Fragmented habitat islands serve as refugia for sensitive species and provide weak and localized or unidirectional sources of colonists to the degraded and relatively hostile matrix. Many refugia are sufficiently distant from others that little successful exchange of individuals between populations occurs, but some migration still occurs between patches that are closely spaced.

to wrongly assume that habitat factors are not the cause of population declines.

Unfortunately, for aquatic ecosystems in North America (and most of the rest of the world), the fragmentation scenario is probably a more realistic representation of the ecological status of most sensitive species. Spatially informed and taxon-specific models, as yet largely undeveloped and untested, will be necessary to understand and predict biotic responses in this kind of landscape. Such models, assuming they can be someday successfully developed, will be complex and highly site-specific in many of their predictions. One of the few general rules of thumb that emerges from preliminary work in this vein is that maintaining existing undisturbed habitat patches (especially large or complex patches, or those with high density or diversity of sensitive species) is critical for maintaining native species biodiversity in altered landscapes (Zwick, 1992; Frissell, 1993b;, Rieman *et al.*, 1993). In other words, continuity through time and space, of both particular habitats and particular populations, is increasingly important in fragmented and human-altered landscapes. If watershed analysis is to become truly effective as a set of tools for biological conservation, it will have to be considerably expanded to explicitly account for these kinds of biophysical and biogeographic relationships.

Although the preceding discussion has stressed the individuality of watershed responses to human disturbance, there is a level of general understanding that can be gained from retrospective analysis of physical and biological histories. However, we suggest this understanding is best gained by a design that includes comparative analysis of multiple watersheds over time, in which some watersheds are heavily impacted by human activities and others are less or differently altered, or affected at different times and places. Spatially and temporally consistent patterns in the response of key assemblages and populations can reveal the presence of general, predictable effects (McAllister and Peterman, 1992) – e.g., that increased sediment reduces survival of fall-spawning salmonids, or that summer water withdrawals reduce survival of specific species and age classes. We believe much more powerful understanding of physical-biological interactions and their ecosystem management implications can generally be gained from the integrated, comparative analysis of multiple watersheds across a regional landscape than from intensive, reductionistic analysis of a single catchment. Such investigations might better be called watersheds synthesis than watershed analysis.

ECOSYSTEM MANAGEMENT IN THE FACE OF UNCERTAINTY, IGNORANCE, AND RISK

We do not intend to discourage or disdain the development of new and more sustainable approaches for environmental management, or in the terms of Regier and Baskerville (1986), sustainable redevelopment. Our fundamental point is that we need new management, but to get it we must change our expectations of management. If ecosystem management is sold with the promise of no net environmental impacts, jobs for everybody, and restoration for every habitat and species, nothing has really changed except the jargon. Should we instead choose to frame ecosystem management as a consciously experimental endeavor with a largely uncertain outcome – an acknowledgment that we have been playing a losing game and if we are not extremely careful with our remaining natural resources, we stand to suffer environmental and eventually economic check-mate – then perhaps we can indeed move forward to a new perspective that provides a clear (if slim) chance for long-term maintenance and restoration of our environment and its aquatic resources.

Most philosophies and approaches for ecosystem management put forward to date are limited (perhaps doomed) by a failure to acknowledge and rationally address the overriding problems of uncertainty and ignorance about the mechanisms by which complex ecosystems respond to human actions. They lack humility and historical perspective about science and about our past failures in management. They still implicitly subscribe to the scientifically discredited illusion that humans are fully in control of an ecosystemic machine and can foresee and manipulate all the possible consequences of particular actions while deliberately altering the ecosystem to produce only predictable, optimized, and socially desirable outputs (Grumbine, 1994; Stanley, 1995; Frissell *et al.*, in press). Moreover, despite our well-demonstrated inability to prescribe and forge institutional arrangements capable of successfully implementing the principles and practice of integrated ecosystem management over a sustained time frame and at sufficiently large spatial scales, would-be ecosystem managers have neglected to acknowledge and critically analyze past institutional and policy failures (Grumbine, 1994; Underwood, 1995; Stanley, 1995). They say we need ecosystem management because public opinion has changed, neglecting the obvious point that public opinion has been shaped by the glowing promises of past managers and by their clear and spectacular failure to deliver on such promises (Frissell *et al.*, in press).

These fundamental limitations on our ability to anticipate and optimize environmental outcomes in ecosystem management are particularly striking in aquatic ecosystems, which are strongly linked and yet spatially and temporally removed from many of the fragmented institutions, human activities, and natural events that affect them. Like Bella and Overton (1972), Regier and Baskerville (1986), Ludwig *et al.* (1993), Stanley (1995), and many other eminent scientists, we emphasize that no foreseeable science or management will eliminate the fundamental challenges and risks posed by uncertainties about future ecosystem response to human actions, and human response to ecosystem changes.

THE NEED FOR WATERSHED RESERVES IN ECOSYSTEM MANAGEMENT

The concept of definition and establishment of large-watershed reserves can provide several crucial functions that are lacking in other, less spatially-explicit approaches to ecosystem management. An ecosystem management plan without reserves is a plan that fails to address what we now know about ecosystems, the state of the environment, and our management capabilities (Stanley, 1995). No plan can eschew or gloss over these issues and still claim to provide a valid map to recovery or maintenance of biodiversity, ecological integrity, and other ecosystem services. In a sense, we are arguing that the world does not face an ecosystem problem; it faces a management problem.

What would a watershed reserve system look like, and how would it help us cope with or avoid management problems? Such reserves would constitute a network of the best-remaining examples of relatively unaltered ecosystems and aquatic communities; in extensively-altered landscapes, these would need to be supplemented or replaced by the least-disrupted ecosystems that retain much of their ecological value and hold good promise for relatively rapid and cost-efficient restoration. In Figure 2 we present a brief example, but we refer readers to several recent sources for deeper discussion of these issues than we are able to provide here (e.g., Reeves and Sedell, 1992; Frissell, 1993b; Frissell *et al.,* 1993; Doppelt *et al,* 1993; Noss and Cooperrider, 1994). Such a reserve network should ideally encompass a regionally representative range of terrestrial and aquatic ecosystem types and natural successional conditions, and incorporate areas that have especially high ecological integrity or natural diversity, high incidence of rare or seriously declining aquatic and riparian species and assemblages, and relatively unimpaired natural-historical catchment-wide biophysical processes and disturbance regimes (Moyle and Sato, 1991; for examples see Henjum *et al.,* 1994; Frissell *et al.,* 1995).

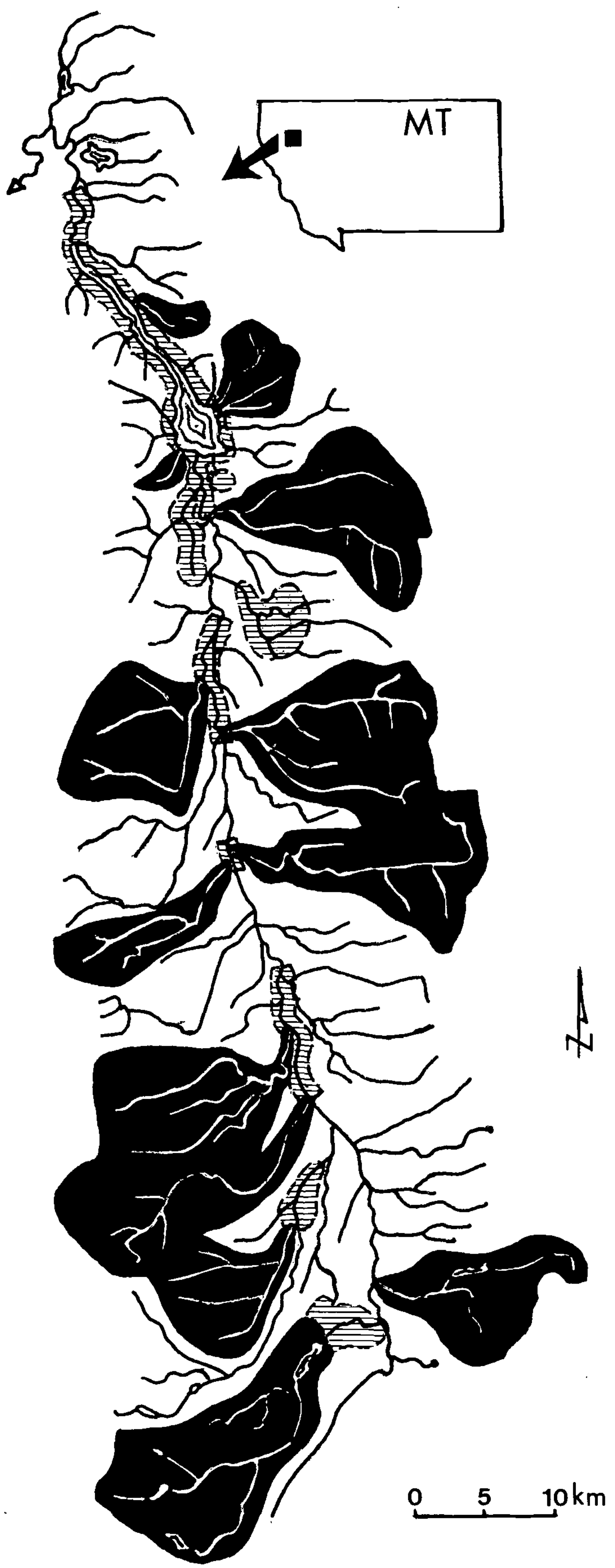

Figure 2. Example of a Recommended Design for an Aquatic Diversity Reserve Network for the Swan River Basin, an Area of 2,070 km2 in Northwest Montana, USA (after Frissell *et al.,* 1995). The figure shows critical watersheds (black tone) and river-lake corridors and wetland complexes (line shaded). Critical watersheds contain relatively well-distributed populations of native fishes, restricted distribution of non-native fishes, and limited fish stocking history. Watersheds selected by biological criteria turned out to be among those least-impacted by land use activities in the basin.

The reserve approach acknowledges there is much uncertainty about the success of future management actions and ensures that some large ecosystems will not be directly exposed to new management manipulations that are bound to have unanticipated and unforeseeable consequences (Bella and Overton, 1972; Ehrenfeld, 1991; Henjum *et al.,* 1994; Stanley, 1995). Watershed reserves offer a fundamentally conservative hedge against uncertainties about the outcome of past and future management in four ways. First, they ensure we won't make the same mistakes everywhere. Second, a network of such reserves could provide necessary and appropriately-scaled scientific controls for the landscape-level experiment that ecosystem management constitutes. For example, such watersheds can be absolutely indispensable in distinguishing the effects of climate change from those of direct landscape alteration in ecosystem research and monitoring. Third, from the aquatic point of view, watershed reserves or aquatic diversity areas represent the best remaining places to focus restoration resources for the near-term, where the likelihood of physical and biological success is greatest, and where the greatest share of threatened biotic resources can be protected with the limited resources that are available (Moyle and Sato, 1991; Frissell, 1993b; Doppelt *et al.,* 1993). Finally, the less-disrupted land-aquatic ecosystems within watershed reserves can serve as our best remaining living models for the development of truly restorative ecosystem management on more severely altered parts of the landscape (Frissell, 1993b; Ebersole *et al.,* in press).

Perhaps the best (however imperfect) example of the formulation and attempted implementation (virtually aborted by Congress in 1995) of a similar strategy at a regional scale we know of is the President's Forest Plan for the national forests in the range of the northern spotted owl (FEMAT, 1993). Exciting proposals exist for bi-national redevelopment efforts in the Great Lakes region (Regier and Baskerville, 1986; Steedman and Regier, 1987), and some large-scale conservation programs in progress in developing countries. Similarly spatially-stratified and conservative management strategies, based on river-floodplain valley segments and smaller-scale land-aquatic units within watersheds (Warren, 1979; Frissell *et al.,* 1986; Jensen *et al.,* 1996), need to be developed for large-river ecosystems (Sparks, 1995) and for landscapes where the spatial extent of prior human development may preclude the establishment of functional whole-watershed reserves (Moyle and Sato, 1991; Doppelt *et al.,* 1993; Frissell, 1993b; Moyle and Yoshiyama, 1994). Smaller-scale refinement of the concept of spatial stratification of risk-taking in management actions, coupled with ecological classifications such as that of Jensen *et al.* (1996), could provide a useful framework for planning and evaluation of ecosystem management activities in the landscape outside of special reserve areas as well.

The concept of conservation reserves, particularly encompassing whole catchments, offers a badly needed logic to more effectively and clearly link watershed analysis, adaptive monitoring, and decisions about the planning and scheduling of human activities, with the goal of reducing long-term uncertainties in ecosystem management while simultaneously minimizing its irreversible consequences to aquatic ecosystem integrity and biodiversity. Contrary to Fitzsimmons (1996), who seems to assume that any landscape-wide strategy for conservation would necessarily be implemented by gestapo-like government control, we believe that conservation of natural resources and the stewardship ethic it entails are not intrinsically threatening to human liberty or economies. Although we often forget to think about it (or choose to ignore it), at many levels the conservation of natural resources in some way serves the interest of every person. We know that other cultures have sustainably inhabited ecosystems for many generations without evolving Biodiversity Police, and it is obvious that such tactics are not long tolerated in most societies. For years we have been discussing the concepts discussed in this paper in public forums, and most citizens (but not all managers) roundly accept them as just plain common sense, a good, conservative, and pragmatic basis to begin discussing cooperative management across the landscape. Serious challenges remain, of course, in visualizing, formulating, implementing, and evaluating actual landscape plans based on these principles, and this is where we should be investing the bulk of our creative energy and dwindling resources.

Ultimately, if ecosystem management attains its goal of widespread ecological sustainability, there could be reduced need for maintaining discrete biodiversity reserves and for spatially focusing restoration activities as hedges against the loss of ecosystemic functions and biodiversity in the remainder of the landscape. Whether this opportunity will come to pass depends critically on our actions today, but remains for our grandchildren to see.

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