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ECOLOGICAL INTEGRITY AND WESTERN WATER MANAGEMENT: A COLORADO PERSPECTIVE

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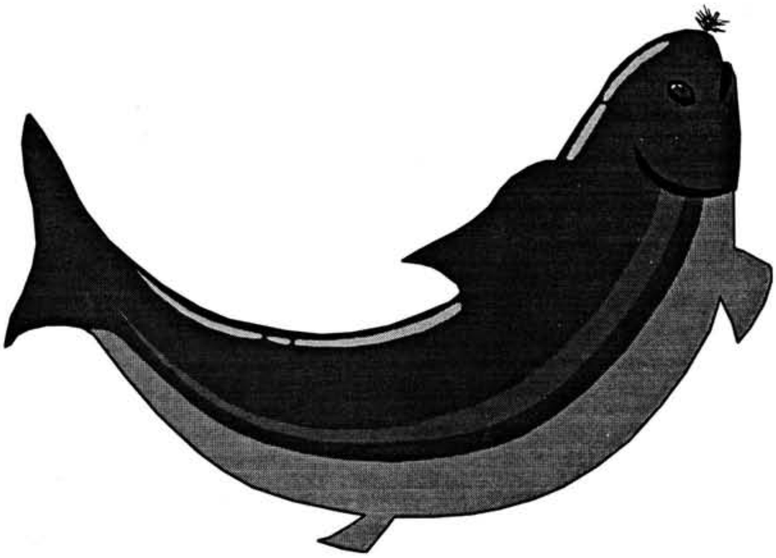

AN OPEN LETTER ON ECOLOGICAL INTEGRITY AND WESTERN WATER MANAGEMENT

Dear Concerned Water User:

This report represents the combined efforts of several faculty at Colorado State University from a wide range of academic backgrounds -- from fishery and wildlife biology to hydrology, engineering, and sociology. We met to discuss our own individual opinions and perspectives on "ecological integrity."

We also discussed these issues with off-campus groups and individuals to gain their insight with aspects of water law, usage in various contexts, and frustrations with current regulations. We found that we shared a number of concerns regarding the importance of increased coordination and communication regarding sustainable resource development.

Too often in the past, groups of concerned citizens and researchers only discussed issues after they confronted a water development project already well along in the planning and implementation phases. In that context the solutions to readily apparent problems of minimum and maximum instream flow, water quality, and recreational use are limited. The need for long-term planning is well established but still not fully appreciated by everyone concerned. If there are opportunities for exchanging ideas, the timing of discussions often seems late in the planning process.

Moreover, the necessity for long-term data and comparative studies of "reference" sites to interpret baseline conditions on a regional scale is not generally understood or appreciated. Some people seem to think we know everything we need to know in order to efficiently allocate water among alternative uses. Others are not concerned with efficiency but with equity and sustainability for future generations. How can we improve and diversify our dialogue? Why attempt to identify and protect some catchments for reference studies?

The concept of ecological integrity is perhaps one means for focusing on ways to measure relative values of managed waterways and compare their value to less managed sites. The importance of rank ordering various habitats regardless of their diverse uses on some continuum from high to low integrity is presented here as a method for measuring how well these habitats can maintain their ecological processes. These fundamental processes such as plant growth, animal reproduction, food-chain functions, and decomposition are likely measures of how well the biota can adapt to changing conditions. These processes are also likely predictors of how well the biota can adapt to changing ecological conditions. These processes are also likely predictors of how these habitats can retain their capacity for self repair whenever conditions are disturbed by some natural event such as drought or flood.

We emphasize that water resources are in ever-increasing demand. As conflicts over alternative uses grow more complex there will be even more need for better understanding of the natural range of variability that characterizes large river basins with their many types of aquatic habitats and land uses. Without a methodology for isolating effects of human use of water from the effects of natural disturbances and long-term variability, we may not be able to agree on how best to use scarce water supplies. Effects of year-to-year variability in precipitation and other climatic variables will continue to need improved technological analyses and to include feed-back loops with human-induced changes in the landscape.

Through the efforts of agriculture extension agents and associated activities, there is a growing awareness among farmers, ranchers, recreationists, and many other water users across the state that we need to use fertilizers and pesticides more carefully, set aside conservation easements to protect floodplains and backwaters, and discuss issues such as flow equalization and water diversions more widely than in the past. Efforts by private groups such as Trout Unlimited, Ducks Unlimited, Audubon Society, the Nature Conservancy, the National Wildlife Federation, and others have all raised important issues and provided solutions for sustaining long-term use of aquatic habitats. State and federal agencies are also working closer together and collaborating with new partners to ensure better coordination and sharing of information. Some of these cooperative efforts build on successful projects that already demonstrate the value of an integrated approach to water resource management. We hope that these successes will continue to attract attention and to broaden the dialogue further. We think that it is important to expand the diversity of views and also to begin to share a common language and set of goals. We hope that this brief report will stimulate discussion and enhance interactions. Let us know what you think. How can we extend this application of team-building and effective partnerships?

Sincerely,

Alan Covich

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EXECUTIVE SUMMARY

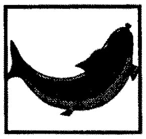
The 1994 reauthorization of the Clean Water Act listed among its purposes: "To assure that water pollution control programs more comprehensively protect the **ecological integrity** of water bodies...through enhanced protection of the physical and biological components of waterbodies." This paper reviews the concept of "ecological integrity" as related to water resources management. Our main goal is to provide physical, biological, and social science perspectives on the definition and measurement of ecological integrity. The intention is to initiate a dialogue to develop an improved understanding of sustainable water resources management.

For our purposes, we propose that: **ecological integrity** refers to an ecosystem where the interconnected elements of physical habitat, and the processes that create and maintain them, are capable of sustaining the full range of biota adapted for that region.

Both the physical processes and the biota are naturally variable in time and space. Settings with high ecological integrity are resilient, and self-correcting when subject to natural disturbance, and their inherent potential is realized without intervention.

Measures of ecological integrity should be based on physical, ecological, and societal relevance and have sensitivity to demonstrate changes above the background variability. Our definition of ecological integrity is an attempt to broaden the scope of how to visualize the connection of water resources to the land. We can best achieve ecological integrity by:

- recognizing all stakeholders and encouraging them to participate in decision making process;
- maintaining a range of variation in maximal and minimal flows of water, nutrients, and energy across different scales of the landscape;
- maintaining watershed function (both physical and biological) by maintaining watershed structure;
- working at the landscape level on a watershed and ecosystem basis before considering other boundaries or jurisdictional constraints;
- subscribing to long term monitoring for physical and biological comparisons with relatively undisturbed settings that serve as baselines for interpreting trends and major changes in local and regional ecosystems;
- recognizing the range of natural variability in physical and biological processes and maintaining flexibility in assessing "surprises" or major departures from steady-state ecosystem dynamics; and
- developing protocols to identify restoration needs, while recognizing and maintaining properly functioning systems.



INTRODUCTION

The Federal Water Pollution Control Act (FWPCA) amendments of 1972 (PL92-500) directed states to identify both point-source and non-point source pollution of surface waters. Point sources are regulated under the National Point Discharge Elimination System which is administered by the Colorado Department of Health. Land-use practices were modified to minimize non-point source pollution and are referred to as Best Management Practices.

The FWPCA amendments and subsequent legislative updates are collectively referred to as the Clean Water Act (Adler et al. 1993). The 1994 reauthorization of the Clean Water Act listed among its purposes: "To assure that water pollution control programs more comprehensively protect the ecological integrity of water bodies...through enhanced protection of the physical and biological components of waterbodies."

There is increased awareness of the essential and valuable nature of freshwater resources (Patrick 1992, Naiman et al. 1995). As various groups organize themselves to respond to diminishing availability of water resources and impoverishment of biotic diversity at the species and ecosystem levels, there is an ever increasing need for ways to discuss differences in interpretations of alternative uses and economic values (e.g., Jackson and Davis 1994, Polls 1994). The recent freshwater imperative provides one example for setting priorities in dealing with these issues (Naiman et al. 1995).

As population pressures increase in the Western United States, there will also be a growing need for a regional perspective that emphasizes the unique conditions that characterize freshwaters in arid regions at high altitude. For example, agreement on national and regional standards for dissolved oxygen may need to consider the importance of oxygen saturation values (as determined by a wide range of extreme temperatures and altitudinal effects of atmospheric pressure) rather than simply referring to concentrations of dissolved oxygen.

This paper reviews the concept of "ecological integrity" as related to water resources management. The main goal is to provide physical, biological, and social science perspectives on the definition and measurement of ecological integrity. We recognize that past or present "natural" ecosystems are not necessarily of higher ecological integrity than "managed" ecosystems. Our purpose is to establish a means for comparing one ecosystem to another while recognizing that each ecosystem is in some sense unique.

We also recognize that ecosystems can change dramatically over time in response to natural and cultural changes within any catchment. What criteria are best for characterizations of catchments in different ecosystems? We suggest that specific abiotic and biotic criteria are useful in describing ecosystem function. The economic costs of alternative management scenarios can be compared in a separate analysis once the abiotic and biotic variables are well understood at the ecosystem level.

Definition of Ecological Integrity

We expanded the original definition of biological integrity (Karr and Dudley 1981) to include physical as well as biological components, because ecosystems are generally defined as the assemblage of organisms in a given area together with the physical factors that form their environment.

For our purposes, we propose that: **ecological integrity** refers to an ecosystem where interconnected elements of physical habitat, and the processes that create and maintain them, are capable of supporting and sustaining the full range of biota adapted for that region.

Both the physical processes and the biota are naturally variable in time and space. Settings with high ecological integrity are resilient, self-correcting when subject to natural disturbance, and their inherent potential is realized without management support.

The concept of ecological integrity incorporates several ideas from previous studies on natural communities and their interactions. Understanding the importance of natural variability among plants and animals as well as the processes that influence their relationships has continued to attract public, philosophic and scientific support (e.g., Karr 1993a, 1993b, 1993c).

A Rocky Mountain - Central Plains Perspective

Much of the research on ecological integrity originated either in the Pacific Northwest or in the eastern regions of North America (e.g., Naiman 1992, Karr 1993b). We propose that in the Rocky Mountains and Central Plains, the relatively young and complex geology, high contrast in topographic relief, water yield efficiency and streamflow modifications, and unique and varying biogeography all must be considered in the management of water resources.

> ***"We do NOT suggest that ecological integrity would be 'better' if we attempted to 'restore' the South Platte to its pre-1850s conditions."***

Rivers in the southwest United States have often been viewed as pipelines or conduits for water transfers rather than as natural habitats for an array of organisms well adapted for fluctuating water levels (Covich 1993).

Reservoirs and human-made canals certainly have aided agricultural production and may also provide new habitats for "naturalized" aquatic species which are often important for recreation. However, natural riverine drainage networks require basin-wide management that also protects native species as well as providing services such as water transport and delivery systems as well as drinking water and recreation. Some catchments are managed for sustainable agriculture, fisheries production, and recreation that often characterize the economic base of this region, while other catchments are managed for nonconsumptive water uses.

In many arid regions where irrigation has helped to increase agricultural productivity there are well documented changes in levels of water tables that have changed riverine and wetland ecosystems, transforming wide intermittent rivers into more narrow channels of permanent flow with resulting changes in riparian communities (e.g., Scott et al. 1993).

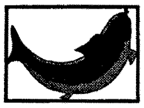
For example, the South Platte River hydrology and riparian ecosystems have changed dramatically in the last 150 years (Eschner et al. 1983, Silkensen 1993). Detailed regional descriptions provide a solid basis for historical comparisons with other regions and for documenting physical and biological effects of water resources management (diversion and irrigation). Studies also identify ecosystem responses to climate, elevation, and geomorphology among regions (e.g., Poff and Ward 1990).

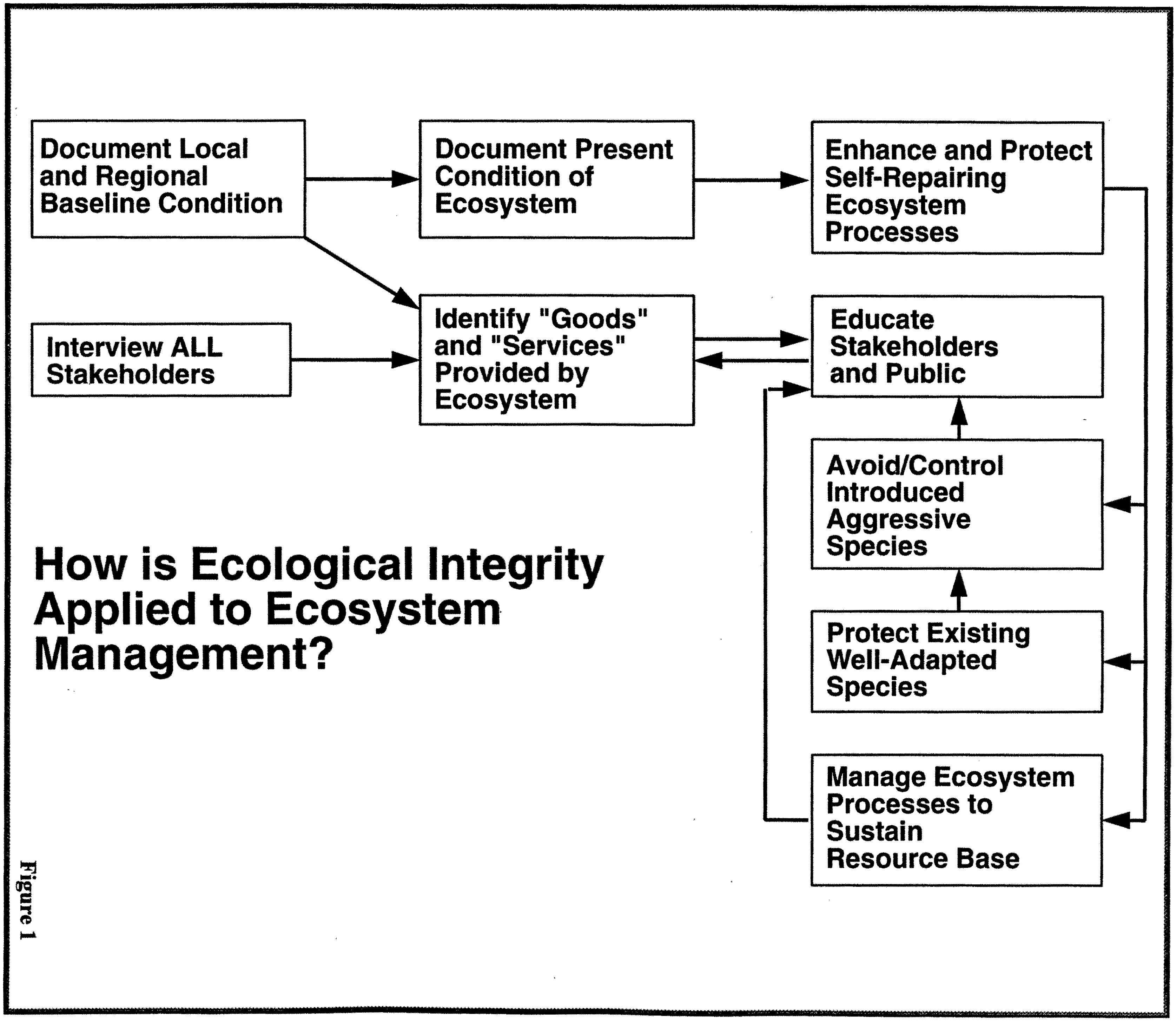
This historical perspective provides some insight in how human use of the land and water has fundamentally changed the original "natural" ecosystem.

We do NOT suggest that the ecological integrity would be "better" if we attempted to "restore" the South Platte to its pre-1850's conditions. However, by having data on some similar, wide, intermittent rivers that do still exist elsewhere and that represent a regional baseline for this type of ecosystem, there is a basis for evaluating and interpreting the ecological integrity of the South Platte River ecosystem. Some sections of the river may be restorable, increasing the level of integrity, while others may be at the highest level possible given the constraints on multiple uses of the basin.

We propose that a working definition of ecological integrity will provide managers a means for using historic and current baseline conditions as a basis for communicating with a wide range of stakeholders (Fig. 1).

Fundamental ecological processes provide unique "goods" and "services" that contribute to the dynamic sustainability of water resources (Naiman et al. 1995). The ecological integrity concept provides a means to inform the general public regarding the importance of protecting and enhancing these processes. Then, the specific relationship among native and non-native species can be evaluated in a broad ecological context rather than on a species by species basis.





How is Ecological Integrity Applied to Ecosystem Management?

Figure 1

MEASURES OF ECOLOGICAL INTEGRITY

The effects of management of natural resources can best be evaluated by comparisons over time and space. Some large drainage areas with minimal management provide a baseline for evaluating regional ecological integrity. These drainages maintain native species and associated ecosystem processes. Examples include the designated "wilderness areas" within national forests or national parks, if they are sufficiently large and continuous to include the full range of natural processes over time and space that characterize that region.

At the other end of the spectrum are highly managed systems (with perhaps a wider range of organisms that are naturalized to these habitats but not necessarily native). Examples of such systems include some irrigation canals, or sections of river downstream from properly designed and functioning sewage treatment plants. These ecosystems can function without continuous and/or high-cost maintenance if they have high ecological integrity.

We suggest that habitats with complex channel structure, backwaters, wide floodplains and an intact riparian buffer zone will continue to provide ecological "goods" and "services" with a minimum of expenditures by management. Once the physical and biological structure of the habitat is modified so that natural floodplains are lost and the riparian buffer zone restricted, there is a relatively greater need for intensive management.

For example, conversion of an unmodified channel and floodplain into a pasture will alter fish and wildlife habitats and lead eventually to a loss of species richness and loss of essential "free" amenities provided by ecosystem processes (Fig. 2). The costs and benefits of this landscape-level alteration can be viewed in terms of relative loss of ecological integrity if continual management is needed to maintain the functions of the river ecosystem.

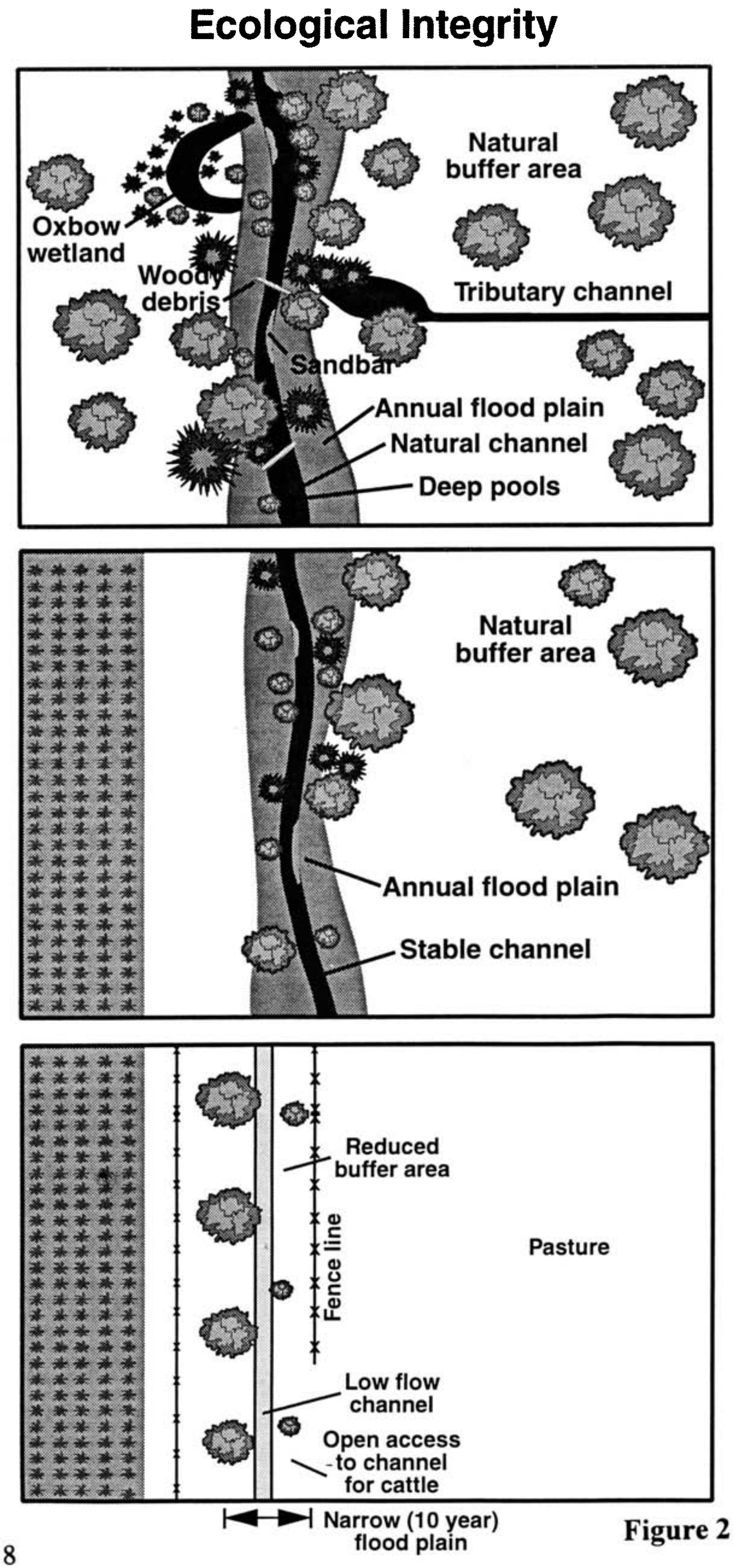


Figure 2

> *"Healthy ecosystems with ecological integrity are characterized by three attributes:*
>
> - *their inherent potential is realized;*
> - *their capacity for self-repair when perturbed is preserved; and*
> - *they require minimal external support from management."*

In contrast a less detrimental shift in landscape management would allow for agricultural production and cattle grazing as long as the riparian buffer were retained and sufficient elements of the natural hydrologic regime and floodplain dynamics persisted. In a well-managed ecosystem there can be a range of land uses that remain sustainable and compatible.

Natural cycles of floods and droughts shape channel morphology (Schumm 1977, Church 1992), and along with fire, ungulate grazing, and insect outbreaks can shape the riparian vegetation which forms much of the habitat complexity on which aquatic biota depend.

Riparian vegetation influences bank stability, bank erosion, and sediment sources. These sediments may affect water quality and habitat conditions for fish and macroinvertebrates (Stednick 1987).

Aquatic species are known to vary in distribution and abundance through time, even in undisturbed streams (e.g., Bramblett and Fausch 1991a, 1991b). Recent research reveals that aquatic organisms have evolved life-history patterns that take advantage of the complex interconnectedness of habitat elements.

One example is the river continuum concept that predicts how aquatic invertebrate communities change along a river as it flows over a large area with varied inputs from riparian vegetation (Vannote et al. 1980).

As a consequence of different channel widths, the shaded upstream tributaries have aquatic insects that shred detritus from inputs of riparian leaves, while the open channels downstream have aquatic insects that filter out fine suspended detritus or graze on algae that derive their energy from the sun. These patterns of biotic distributions and upstream-downstream linkages are altered by construction of large dams and water diversions as well as by land uses (Stanford and Ward 1992).

As another example, many aquatic invertebrates disperse downstream by drifting with stream flow as part of their life history. Likewise, adults of stream fishes ranging from small minnows in Great Plains streams (Winston et al. 1991) to the large Colorado squawfish, *Ptycocheilus lucius,* in the Colorado River (Carlson and Muth 1989) migrate upstream tens to hundreds of kilometers to spawn, with concomitant downstream drift of juveniles to facilitate dispersal to rearing areas that are often in temporary floodplain or backwater habitats. The high incidence of movement across habitat boundaries by various aquatic biota argues for inter-connectedness as a key issue in ecological integrity (Covich 1993).

Healthy ecosystems are thought to be characterized by resiliency to and relative predictability following disturbance (Rapport 1989, Costanza et al. 1992). Healthy ecosystems with ecological integrity are characterized by three attributes:

- their inherent potential is realized;
- their capacity for self-repair following perturbation is preserved; and
- they require minimal external support from management.

In contrast, aquatic ecosystems that lack integrity often require expensive management to ensure continued beneficial uses such as fisheries production, recreation, and clean drinking water.

ATTRIBUTES FOR ASSESSING ECOLOGICAL INTEGRITY

Ecological integrity includes five important elements:

- maintaining both natural variability and inter-connectedness of physical habitat within large continuous spaces and along those corridors that are essential for the migration and dispersal by native biota.
- maintaining native species whenever and wherever those plants and animals still remain in their natural habitats;
- providing for restrictions on those "naturalized" species so as to limit their dispersal and expansion of distributions into areas where they may disrupt naturally sustainable ecosystems;
- establishing long-term monitoring of essential ecosystem attributes over large, spatially heterogeneous areas to evaluate quality of both micro- and macro-habitat; and
- providing science-based management options to the public and natural resource agencies in a timely manner.

Metrics for ecological integrity may include physical, biological, and social criteria and are yet to be defined, but these categories are essential for the quantification of ecological integrity. We recommend that measures of ecological integrity include:

- Physical Relevance -- What is the importance of the measurement to the overall process creating and maintaining that environment? An example of a physically relevant process would be the occurrence of overbank flows to create a seedbed for streamwide vegetation.
- Ecological Relevance -- What is the importance of the measurement to the overall structure and function of the ecosystem being assessed? An example of an ecologically relevant measurement would be abundance of a keystone species (e.g., a species that has a significant influence on the structure and function of an ecosystem that is disproportionate to its relative abundance).
- Societal Relevance -- What is the importance (socioeconomic, political, cultural) of the measure to the general public and decision makers? Examples of such measures of societal relevance include economically important species or threatened and endangered species (e.g., Colorado squawfish).
- Sensitivity/variability -- How sensitive is the measurement relative to the amount of natural variability? This criterion is primarily an assessment of the "signal-to-noise" ratio of the criteria being measured.
- Cost effectiveness -- What are the costs associated with these measurements? Because of the high costs associated with collecting ecological data and because it may be necessary to collect these data routinely by local, state and federal agencies, monitoring should be evaluated based on costs associated with data collection and analysis.

Physical Attributes

Implicit in the definition of ecological integrity is the concept that specific physical measures can be used to assess the ability of an watershed to create and maintain the physical template for the biological resources. Stream habitat or channel stability assessments have been developed both as an inventory and a metric to determine future or potential land use activities.

Recognition of the interconnectedness between hillslope processes and the stream channel has led to various watershed assessment procedures (Stednick, in press). In general, the watershed assessment procedure is a systematic approach to assess the natural sensitivity of a watershed, the present hydrologic condition of the watershed, and the hydrological implications of proposed (or existing) land use activities and management.

Several studies have related fish abundance (or productivity) to stream width, water depth, pool volume, and streamflow regime. The cross section of a stream channel provides information on determining total space available for fish and the annual variability of this space related to streamflow and channel morphology. Riparian or streamside degradation may result in channel widening. The often narrow and deep channel structure represents a stream type capable of supporting both in-stream and streamside biota. The change in width and depth can lower the local water profile and exacerbate the degradation of streamside vegetation and decrease low-flow conditions.

Narrow and deep stream profiles are less variable between high and low stream discharges and thus provide more continuous habitats for fish and macro-invertebrates. Measures of stream morphology include: width, depth, width:depth ratio, bankfull channel width and depth, low-flow channel, and substrate size. The substrate size (stream bottom sediments) can be used to quantify sediment transport capacity and is often used as a surrogate for channel stability. The channel stability metrics used by federal agencies include substrate size, channel dimensions, riparian vegetation and large woody debris. The stability ranking or category is usually related to sediment transport potential.

Spatial and Temporal Variation in Physical Attributes

Channel dimensions vary as a function of stream discharge (Church 1992). Stream discharge generally increases with increased drainage basin area (or longitudinal distance). However, there are significant hydrologic modifications on many Colorado rivers. These modifications include dams and reservoirs for storage and release as well as trans-basin diversions. Spatial and temporal variation in stream discharges must be recognized.

The streamflow generation and routing mechanisms must be considered as processes that create and maintain the biological habitat template. Systems with ecological integrity often have overbank flows that influence channel morphology and streamside vegetation. The connectivity between the stream floodplain and the stream channel should be maintained; indeed, stream restoration efforts often focus on this linkage.

The streamflow generation and routing mechanisms also influence water quality. For example, streamflow generated by overland flow (when precipitation rates exceed infiltration rates) often has high suspended sediment concentrations and carries sediment associated contaminants. The overland flow component also has a flashy response, quick time to peak, high peakflow, and a quick return to baseflow (or no flow) conditions.

Quantification of streamflow generation and routing mechanisms can be done by understanding the hydrologic modification schedule and evaluation of peakflow to low-flow ratios, or flow-duration curves.

Biological Attributes

Implicit in the definition of ecological integrity is the concept that specific biological measures will be used to assess the ability of an ecosystem to support and maintain the "full range of biota adapted for a region."

The quantitative characterization of biological communities to measure persistence and sensitivity of stream ecosystems includes the distribution and abundance of diatoms (Patrick 1992), protozoans (Cairns 1977), macroinvertebrates (Clements et al. 1989, Clements and Kiffney 1994, Clements 1994) and fish (Karr et al. 1987, Fausch et al. 1990).

These biological measures may have advantages over routine chemical analysis of water quality and should be included any assessment of ecological integrity. Stream biota integrate changes in exposure conditions over time and may provide a continuous monitor of water quality (Clements and Kiffney 1994).

Recent studies have examined the efficacy of several community- and ecosystem-level indices for assessing effects of anthropogenic disturbances in streams (Clements 1994). It is unlikely that all measures of ecological integrity employed in other regions of the country will be useful in western states, particularly Colorado.

It is unlikely that sensitive, cost-effective, biologically and socially relevant measures with low natural variability will be found. Therefore, proposed measures should be evaluated based on each of these criteria. Measures with high biological and societal relevance should have high priority. However, a measure with social and ecological relevance will be of little use if it is highly variable and cannot distinguish between background and disturbed locations.

Criteria at different levels of biological organization

Criteria used to assess ecological integrity may be selected from any level of the hierarchy of biological organization (e.g., molecules, cells, tissues, organs, individuals, populations, communities, and ecosystems). Measurements at lower levels of organization (e.g., biomarkers) may be sensitive and cost effective; however it is unlikely that these criteria will be ecologically or socially relevant. Therefore, we recommend that biological criteria for assessing ecological integrity be based on population, community, and ecosystem responses to disturbance.

Population-level measures may include estimates of population density, biomass, population growth rates, age structure, sex ratio, and genetic structure. As a result of research on the management of species of commercial or recreational importance, sophisticated population models have been developed that predict changes in these measures as a result of perturbations.

Community-level criteria have probably been used the most to assess ecological integrity. Typical structural measures of anthropogenic disturbances include reduced abundance, reduced species richness, and a shift in community composition from sensitive to tolerant species.

More sophisticated community-level indices have been derived from these data, based on the assumption that a shift in community composition at disturbed locations relative to reference locations is an indication of the degree of disturbance. Three general types of indices derived from community-level data include species diversity indices, similarity indices, and biotic indices.

Species diversity indices, such as the Shannon-Wiener function (H) or Simpson's index of diversity (D), integrate measures of species richness and the abundance of individuals within each species (e.g., evenness). Low diversity values at disturbed locations result from either low species richness and/or low equitability of the distribution of individuals among species (Metcalfe-Smith 1994).

Although these indices are useful for assessing impacts of organic enrichment, their applicability to other types of disturbance (e.g., flow alterations, toxic materials, introduction of exotic species) is uncertain. Furthermore, while reasonably accurate estimates of relative abundance may be obtained by field sampling, estimates of species-specific sensitivity to disturbance are considerably more difficult to obtain.

Ecosystem-level measures of ecological integrity generally include functional measures, such as primary and secondary productivity, nutrient cycling, energy flow, and detrital processing (Rapport 1989). As with population- and community- level criteria, the usefulness of these measures will probably vary among ecosystems.

The general ecosystem-level responses to stress include both structural and functional measures (loss of nutrients, decreased primary productivity, reduced species diversity, reduction in the size of organisms, and shifts in community composition).

The most comprehensive studies of ecosystem responses to perturbations have been whole-ecosystem manipulations (e.g., Schindler 1987). One of the more consistent results of these studies is the finding that indirect effects are often more significant than direct effects. For example, whole-lake acidification studies (Schindler et al. 1985) demonstrated that reduced prey abundance had a greater effect on lake trout populations than direct toxicological effects of reduced pH.

The relationship between structural (primarily community-level assessments) and functional (ecosystem-level assessments) measures has been discussed

(Metcalfe-Smith 1994). Although functional measures integrate responses of populations and communities, some researchers have noted that functional measures are less sensitive and more variable than structural components (e.g., Schindler 1987).

Furthermore, because of functional redundancy of ecosystems (e.g., one species may replace another species without disruption of ecosystem function), structural changes may occur without immediate changes in ecosystem function.

Spatial and Temporal Variation in Biological Criteria

As noted in the definition of ecological integrity, biological systems are naturally variable in space and time. Consequently, effects of disturbance on measures of ecological integrity are confounded by natural variation.

One of the key challenges in assessing ecological integrity is distinguishing effects of anthropogenic disturbances from natural variation in ecosystem structure and function. This distinction will be especially difficult when evaluating the integrity of moderately-impacted systems and those with cumulative effects or inadequate long-term studies.

Distinguishing natural variation from anthropogenic effects may be accomplished by selecting criteria that are less sensitive to natural changes but highly sensitive to anthropogenic disturbances (e.g., have a high signal to noise ratio). As an example, in lotic systems small-scale differences in current velocity, substrate composition, and the nature of the riparian habitat influence ecosystem structure and function.

On a larger scale, variation in abundance and species diversity, from headwaters to low-elevation streams is well documented (Vannote et al., 1980). This spatial variation is particularly severe in western streams, where longitudinal changes occur over relatively short distances along the stream channel. (Ward and Stanford 1983).

Species richness and diversity, two measurements frequently employed to assess ecological integrity, generally increase from headwater streams to low-elevation streams. Consequently, it is difficult to separate effects due to disturbance from natural longitudinal changes in these measures.

Temporal seasonal variation of aquatic ecosystems also confounds assessments of ecological integrity. Seasonal variation in aquatic communities and interactions between hydrologic conditions and biological measures must be considered when assessing ecological integrity. For example, in streams impacted by mining operations, effects of heavy metals on aquatic communities are greater during the period of spring runoff because of increased metal concentrations (Clements 1994).

Social Attributes

Small-scale irrigation systems, rangeland conservation areas, urban-fringe greenbelts, as well as large river basins, all have economic, social and political dimensions that are central to their functioning as ecologically integrated systems. These dimensions represent a web of economic wants, social values, and political goals that relate to maintenance of the natural resources and ecological integrity.

Most natural systems today are social systems, and the ecological integrity of the natural system is dependent upon key attributes of the social system woven through it.

Social systems that lack an avenue for adequate public involvement in natural resource management issues generally do not have the capability of maintaining ecological integrity.

Social systems that lack educational processes which effectively feed back information about the pattern of resource utilization and its consequences are usually not sustainable.

Finally, social systems that are in conflict regarding agreed- upon methods of resource management may not be able to plan effectively to achieve any degree of ecological integrity.

Central to moving in the direction of an ecologically integrated river basin or watershed area, then, is creating local capacity for public involvement, educational processes and conflict mitigation.

Once this capacity has been targeted for improvement or development, the social system then begins to mobilize itself to form locally sustainable organizations that can finance and regulate such groups. Locally financed conservation organizations or associations may possess various degrees of governmental powers, depending upon the nature of the problems associated with the group.

"Ecological integrity is a condition or state reflecting both natural and social dynamic equilibria."

Ecological integrity is a condition or state reflecting both natural and social dynamic equilibria. The definition of a desirable natural state, one that generally meets the definition of sustainability, may change with improved knowledge of its various components. Likewise, the social system associated with it is generally undergoing constant change in its emphasis on alternative uses.

Knowledge of a species habitat, or a paradigm shift in interpreting natural populations, may change the definition of ecological integrity for a particular group. Economic shifts may place new emphasis on resource use, or raise or lower existing patterns of use. In doing so, the need for public involvement, education and conflict management may shift.

Social equity must be acknowledged when gauging the most desirable state of equilibrium. The social and economic costs associated with restoration, maintenance, and possible regulatory measures insuring ecological integrity should not be unfairly borne by particular segments of the community. Sanctions against undesirable use must be fairly administered. All of these social conditions must generally be present if any group is to achieve ecological integrity.

This social and natural integration is the measure of the degree to which the natural state can be maintained over any extended period of time. It is virtually impossible to separate the social web from the natural system. We are generally left with organizational devices designed to help find our way clear of natural disequilibrium. Although natural scientists can provide useful tools to assess the general baseline for the ecological integrity of natural ecosystems, the social scientists also has an important role. The social technologies for maintaining sustainable ecosystems involves various strategic social arts, of which organization appears to be the most critical. How we organize, and how effective our organizations are, will determine the degree to which the knowledge of the natural scientist will help us achieve ecological integrity.

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MEASURABLE PARAMETERS OF ECOLOGICAL INTEGRITY

Watershed Conditions

Initially, only three components are needed as a first approach to assess a watershed's physical state: water runoff patterns, sediment transport, and riparian conditions.

The interrelationships among runoff patterns, sediment transport, and riparian condition are complex, but recognized as important influences on fish habitat, water quality, channel stability, macroinvertebrate habitats, and eventually beneficial uses of the waters. The complexity of these interrelationships is further compounded by the diverse stream systems found in the southwestern United States.

Water Runoff Patterns

Channel form and function are influenced by the amount and timing of water conducted by the channel. Stream energy (streamflow) is in balance with sediment transport. Increased streamflows may increase sediment transport, conversely streamflow decreases may decrease sediment transport. Modified streamflows (hydrologic diversions) modify stream form and function, both in-channel and stream bank.

Sediment

Sediment transport affects turbidity, stream substrate, macroinvertebrates, pool depths, water temperature (and dissolved oxygen), and channel form and function, particularly streambank stability and pool riffle development and maintenance.

Riparian Condition

Riparian areas influence stream-bank stability, water temperature, nutrient sinks or sources, upslope sediment input, macroinvertebrate food supply, and fish habitats (snags). Riparian vegetation in forested environments also provide large woody debris and consequently in-channel sediment storage associated with debris dams.

Benthic Macroinvertebrates

Biological measurements used to assess ecological integrity have been developed for several groups of aquatic organisms, including protozoans, periphyton, macroinvertebrates and fish. Owing to taxonomic and other logistical difficulties, the use of protozoan and diatom communities for assessing ecological integrity is limited.

The use of benthic macroinvertebrate communities to assess biological integrity of streams has a long history (Hynes 1970, Allan 1995). Several recent reviews have reported the usefulness of benthic communities for assessing changes in water quality (e.g., Metcalfe-Smith 1994).

Because of their influence on various functional parameters in streams, such as primary productivity, detritus processing, and energy flow, changes in abundances and distributions of benthic macroinvertebrates have the potential to reflect changes in stream ecosystems. In addition, because benthic macroinvertebrates are the major prey of many species of fish in Colorado, they also have societal relevance in terms of recreation and biodiversity.

Costs of measuring changes in benthic macroinvertebrate communities may be initially higher than those associated with physical and chemical variables. However, identification of indicator species assemblages for specific classes of disturbances (Clements 1994) and the development of rapid bioassessment protocols using benthic community metrics (Resh and Jackson 1992) have reduced costs.

Finally, some measures of benthic community structure are highly sensitive to disturbance and are highly cost-effective because they have relatively low variability.

Fish Communities

Fish communities are useful to assess environmental degradation and indicate the relative health of ecosystems. Indices of species diversity derived from information theory were widely used during 1960-80 (see Washington 1984 for review), but have many drawbacks (Fausch et al. 1990). Karr (1991) developed a composite measure, the index of biotic integrity (IBI), based on 12 attributes of fish assemblages that reflect important changes in their structure and function as water resources are degraded (Karr et al. 1986).

The index has wide flexibility due to its broad ecological scope, and has been adapted for various regions (e.g., Fausch et al. 1984, Lyons 1992). Because of low species diversity of fish in Rocky Mountain streams, the IBI may be of limited use in Colorado.

Fish Populations

Despite the problems encountered in attempts to apply the IBI to eastern Colorado plains streams (Schrader 1989, Bramblett and Fausch 1991b), several parameters are likely to be useful as indicators. The number of native species has been repeatedly found to be the best single metric of ecological integrity (Angermeier and Karr 1986, Karr et al. 1987).

The use of fishes to assess ecological integrity in habitats that have only a few fish species, such as coldwater streams where three or four species of trout, suckers, and minnows are native, is best done by considering the individual populations involved, or even finer levels of resolution such as physiological stress (see reviews in Adams 1990).

Moreover, if it is determined that sport fish management is an appropriate goal, and is compatible with management for a sustainable ecosystem, then other more specific objectives can be integrated with the ecological integrity goal.

> ***"Ecological integrity can best be assessed when teams of expert biological and physical scientists work together so that each is using his or her expertise in an integrated fashion and not relying solely upon some formula for quantifying complex, dynamic relationships."***

The exotic species introduced in Colorado to date have generally been unable to thrive in flowing waters of the eastern plains, but are among the most important factors affecting native species in the Rio Grande and Colorado River basins. Therefore, the percent of exotic species captured is also often a useful metric (Schrader 1989).

The percent of individuals that are omnivorous species, or the percent of individuals that are tolerant species, are also often useful indicators of altered systems. Because both food resources, and physicochemical conditions, may fluctuate widely after streams are degraded, highly adaptable and tolerant species often dominate in degraded environments.

However, omnivores and tolerant species also dominate in naturally variable environments, such as many sites in the Arkansas River basin (Bramblett and Fausch 1991b), indicating that these measures must be compared to levels at relatively undisturbed sites in the region.

Research in the Purgatoire River in the Arkansas basin, one such undisturbed site, suggests that omnivorous, tolerant species were abundant in naturally fluctuating systems (Bramblett and Fausch 1991b, Fausch and Bramblett 1991).

Fish as "Canaries"

A final attribute that is likely to be a useful indicator of ecological integrity pertains to condition of individual fish. Fish in highly degraded environments often display increased disease, parasitism, and deformities as a result of chronic exposure to pathogens or toxic chemicals.

Care again must be taken to determine natural background levels for comparison, and to ensure that the diseases monitored are a result of degraded water quality or habitat for fishes, and not lack of habitat for invertebrates that are intermediate hosts for parasites (cf. Fausch et al. 1990).

Perhaps the most important ingredient to ensure successful and prudent biomonitoring using fishes or other biota is a qualified, experienced aquatic ecologist. Ecosystems are complex entities that require long-term data for a thorough understanding of ecological and physical principles.

Ecological integrity can best be assessed when teams of biologi-cal and physical scientists work together so that each is using their expertise in an integrated fashion and not relying solely upon some formula for quantifying complex, dynamic relationships. Although managers need some means of monitoring changes, simple indices have not proven useful for many types of decision making affecting large ecosystems.

Evaluation of Colorado's Stream Fishes

Flowing waters in Colorado present special problems when attempting to use the index of biotic integrity, although the ecological basis for it is still expected to apply.

For example, the index is based on the assumption that as streams are degraded, the number of native species will decline. However, as a result of the harsh physicochemical conditions present in western Great Plains streams (e.g., East Slope plains streams) and in the Colorado River (West Slope) and Rio Grande basins, most remaining native species are expected to be relatively tolerant to perturbations that mimic the natural variations in flow, temperature, turbidity, and associated physicochemical factors.

Thus, fishes that were able to withstand the rigors of life in plains streams of eastern Colorado in their original state, when flow and temperature fluctuated markedly in the annual cycle, may also be well adapted to withstand added anthropogenic-flow and temperature fluctuations. Presumably, the most degrading change in these streams would be to suddenly introduce a constant flow of clear, cold water in summer months, such as might be released below a large reservoir.

This previous statement does not mean to imply that no fish species sensitive to environmental perturbations were present in eastern Colorado plains streams. Several species with wide geographic distribution, such as the lake chub *(Couesius plumbeus,* Bestgen et al. 1991) and northern redbelly dace *(Phoxinus eos,* Bestgen 1989), are found in small enclaves of habitat in the cool foothills or transition zone reaches of Front Range streams, and are thought to be glacial relics from cooler and wetter post-glacial periods.

Several other such species have been locally extirpated during the last 140 years (cf. Propst 1982, Propst and Carlson 1986). Although none of these was known to be a unique species, genetic diversity in locally adapted populations was certainly lost, such as described above for the walleye or sauger once present. An even more important problem than the generally depauperate and tolerant fish fauna is the lack of data and understanding to allow intelligent biomonitoring in these systems. For example, irrigation and degradation of aquatic habitats associated with irrigated agriculture began on Colorado's eastern plains in the 1860s, and were well established by 1900 (Eschner et al. 1983).

In contrast, fish were collected from less than 25 locations in the entire South Platte basin before 1914 (Kevin Bestgen, CSU Larval Fish Laboratory, pers. comm.), which makes it extremely difficult to assess what fauna were native and which sensitive species were lost before sampling could detect them. Moreover, in contrast to lotic systems in the midwestern and eastern United States, relatively little is known about how aquatic ecosystems in the western Great Plains and Great Basin should operate (Matthews 1988), making it difficult to develop indices that are based on assumptions about how they respond to degradation (e.g., Bramblett and Fausch 1991b).

POTENTIAL IMPACT ON REGIONAL WATER USERS

Traditionally, the management or development of regional water resources has been directly linked to the project benefits and costs. The direct impacts of water resource development on the ecosystem were not perceived as a major societal concern. Any disruption of the physical habitat was considered a small price compared to the users' need of water.

The infrastructure needed to support the distribution of water has primarily been evaluated in terms of how the adjacent ecosystem affects the human-made physical features. The infra-structure design has tended to focus on the functionality and efficiency of the project often ignoring how the project potentially impacted the ecological integrity.

Now that ecosystem integrity is being elevated to a level that is at or near the importance of the project physical features and financial return, the water users may be impacted not only financially, but also in the manner of how routine business is conducted.

For example, many water projects are developed by diverse teams comprised of biologists, hydrologists, engineers, sociologists, and other project-specific specialists. The team approach to project development provides comprehensive project planning, and assessment of project impacts.

As ecological sensitivity increases the request to develop water projects may impact the water users (e.g., Loomis 1993). Many instream structural features are not advantageous to maintaining a natural equilibrium of the ecosystem. New structures and features will have to be developed and evaluated before short-term and long-term impacts can be assessed.

Further, the passage of more stringent legislation may force the water user to demonstrate how natural equilibrium of the ecosystem can be maintained while implementing and operating the project before approvals and permits will be issued.

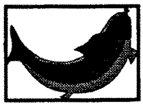
For water managers and direct users, the definition of ecological integrity represents an interdisciplinary effort to bring together varied groups regarding long-term management of water resources. These groups share a common concern with the general protection of a community's historical investment in augmenting or modifying natural resources.

There does not appear to be any real incompatibility between the stated or implied objectives of this definition and current resource use objectives. Other areas of natural resource management, such as soil management to reduce erosion, have undergone consider-able modification in their definition over time without having negatively impacted overall resource use objectives. Most people would agree that a broadened definition of soil management has greatly enhanced these objectives and increased resource sustainability.

Most water managers or users have traditionally attempted to achieve multiple objectives in their management practices, if for no other reason than such methods have been proven to reduce the costs of water development and management in general.

The definition of ecological integrity is in many ways an attempt to broaden the traditional meaning of land and water stewardship. Over time, the costs of water resource management may increase. Equity in the burden of cost appears as a more central issue than major changes in productive uses.

Whether it is ecological integrity or some other concept, we will be challenged mostly in our ability to organize effectively to pay for this expanded management. If there is any impact at all on regional water users, it will be the challenge to redesign our organizations in such a way that we can accomplish these objectives in the most economically feasible and equitable way.



Summary

The definition of ecological integrity is intended to initiate an improved understanding of sustainable water resources management. The ecological integrity concept is an attempt to broaden the scope of how to visualize the connection of water resources to the land and to broaden the traditional meaning of natural resources stewardship.

Whenever possible from an economic and societal perspective, we can best achieve ecological integrity by:

- maintaining natural flows of water, nutrients, and energy across different scales;
- maintaining watershed function (both physical and biological) by maintaining watershed structure;
- working at the landscape level on a watershed basis before considering jurisdictional boundaries;
- subscribing to long-term monitoring with physical and biological comparisons among relatively undisturbed settings to establish a baseline for regional and local interpretations of ecosystem changes;
- developing protocols to identify restoration needs, but recognizing and maintaining properly functioning systems;
- recognizing all stakeholders and encouraging them to participate in decision making process; and
- recognizing variability in physical and biological processes and maintaining flexibility in assessing "surprises" or major departures from regional steady-state dynamics.

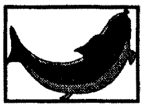
Many of these goals cannot be quantified until additional information is obtained. We know little about how aquatic ecosystems in the Great Plains and Great Basin are expected to operate. A case in point is that perhaps wide fluctuations in fish species richness and abundance are the norm, rather than an aberration as might be assumed.

Although some fish populations in Colorado rivers have been extensively sampled, such as those in trout streams statewide, we know little of the distribution and abundance in many environments, especially on the eastern plains. This informa-tion gap was reflected in past listings of certain fishes as species of special concern, even though some were locally abundant. Recent work by the Colorado Division of Wildlife is aimed at correcting this lack of data.

We know relatively little about the ecology of some fish species in Colorado, including what they eat, where and when they spawn, and other important aspects of their biology. Indices cannot be adequately developed without this basic information.

Sediment inputs and transport rates from watersheds with and without land use activities are not known for all ecosystem types in Colorado. The concept of channel maintenance flows, streamflows necessary to maintain sediment transport and streamside vegeta-tion, was examined in a recent water court trial between the federal government and water providers. From our perspective, one of the key issues of the trial was the lack of a coordinated system for water resources data collection and distribution.

Coordination is a necessary component of ecological integrity and water resources management. Data are often collected by state and federal agencies, and academia with little coordination. Current efforts by the Colorado Natural Heritage Inventory at Colorado State University are focused on increased integration of data from numerous sources into a Geographical Information Systems analysis. Monitoring will be a key component of any approach to ecological integrity. The state must be prepared to take the lead role in monitoring.



References

Adams, S. M. ed. 1990. Biological indicators of stress in fish. American Fisheries Society Symp. 8.

Adler, R. W., J. C. Landman and D. M. Cameron. 1993. The Clean Water Act 20 years later. Island Press, Washington, D.C.

Allan, J.D. 1995. Stream ecology: structure and function of running waters. Chapman and Hall, London.

Angermeier, P. L. and J. R. Karr. 1986. Applying an index of biotic integrity based on stream fish communities: considerations in sampling and interpretation. North American Journal of Fisheries Management 6:418-429.

Bestgen, K. R. 1989. Distribution and notes on the biology of the northern redbelly dace, *Phoxinus eos,* in Colorado. Southwestern Naturalist 34:225-231.

Bestgen, K. R., K. D. Fausch and S. C. Riley. 1991. Rediscovery of a relict southern population of lake chub, *Couesius plumbeus,* in Colorado. Southwestern Naturalist 36: 125-127.

Bramblett, R. G. and K. D. Fausch. l991a. Fishes, macroinvertebrates, and aquatic habitats of the Purgatoire River in Pinon Canyon, Colorado. Southwestern Naturalist 36:281-294.

Bramblett, R. G. and K. D. Fausch. l991b. Variable fish communities and the index of biotic integrity in a western Great Plains stream. Transactions American Fisheries Society 120:752-769.

Cairns, J. 1977. Quantification of biological integrity. IN: The integrity of water. U.S. Environmental Protection Agency, Office of Hazardous Materials, Washington, D.C.

Carlson, C. A. and R. T. Muth. 1989. The Colorado River: lifeline of the American southwest. Canadian Special Publication of Fisheries and Aquatic Sciences 106:220-239.

Church, M. 1992. Channel morphology and typology. pp. 126-143, IN: P. Calow and G. E. Petts (eds.). The rivers handbook. vol. 1. Blackwell Scientific Publications, Oxford.

Clements, W.D. 1994. Benthic community responses to heavy metals in the Upper Arkansas River Basin, Colorado. Journal of the North American Benthological Society 13:30-45.

Clements, W. H., D. S. Cherry and J. Cairns, Jr. 1989. The influence of copper exposure on predator-prey interactions in aquatic insect communities. Freshwater Biology 21:483-488.

Clements, W. H. and P. M. Kiffney. 1994. An integrated approach for assessing the impact of heavy metals at the Arkansas river, Co. Environmental Toxicology and Chemistry 12:1507-1517.

Costanza, R., B. Norton and B. Haskell (eds.). 1992. Ecosystem health: new goals for environmental management. Island Press, Washington, D.C.

Courtemanch, D. L., S. P. Davis and E. B. Laverty. 1989. Incorporation of biological information in water quality planning. Environmental Management 13:35-41.

Covich, A. P. 1993. Water and ecosystems. pp.40-55, IN: P. H. Gleick (ed.). Water in crisis. Oxford University Press, Oxford.

Eschner, T. R., R. F. Hadley, and K. D. Crowley. 1983. Hydrologic and morphologic changes in channels of the Platte River basin in Colorado, Wyoming, and Nebraska: a historical perspective. U.S. Geological Survey Prof. Paper 1277-A. 39 p.

Fausch, K. D., J. R. Karr and P. R. Yant. 1984. Regional application of an index of biotic integrity based on stream fish communities. Trans. Am. Fish. Soc. 113:39-55.

Fausch, K. D., J. Lyons, J. R. Karr and P. L. Angermeier. 1990. Fish communities as indicators of environmental degradation. American Fisheries Society Symposium 8:123-144.

Fausch, K. D. and R. G. Bramblett. 1991. Disturbance and fish communities in intermittent tributaries of a western Great Plains river. Copeia 1991:657-672.

Hynes, H. B. N. 1970. The ecology of running waters. University of Toronto Press, Toronto.

Jackson, S. and W. Davis. 1994. Meeting the goal of biological integrity in water-resource programs in the US Environmental Protection Agency. Journal of the North American Benthological Society 13:592-597.

Karr, J. R. 1991. Biotic integrity: a long-neglected aspect of water resource management. Ecological Applications 1:66-84.

Karr, J. R. 1993a. Protecting ecological integrity: an urgent societal goal. Yale Journal of International Law 18 (1): 297-306.

Karr, J. R. 1993b. Measuring biological integrity: lessons from streams. pp.83-104, IN: S. Woodley, J. Kay and G. Francis (eds.) Ecological integrity and the management of ecosystems. St. Lucie Press, Delray Beach, Florida.

Karr, J. R. 1993c. Defining and assessing ecological integrity: beyond water quality. Environmental Toxicology and Chemistry 12:1521-1531.

Karr, J. R. and D. R. Dudley. 1981. Ecological perspective on water quality goals. Environmental Management 5:55-68.

Karr, J. R., P.R. Yant, K. D. Fausch and I. J. Schlosser. 1986. Assessment of biological integrity in running water: a method and its rationale. Illinois Natural History Survey, Special Publication No. 5, Champaign, Illinois. 28 pp.

Karr, J. R., P. R. Yant, K. D. Fausch and I. J. Schlosser. 1987. Spatial and temporal variability of the index of biotic integrity in three midwestern streams. Trans. Am. Fish. Soc. 116:1-11.

Levitt, B. and J. G. March. 1988. Organizational learning. Annual Review of Sociology 14:319-340.

Loomis, J. B. 1993. Integrated public lands management. Columbia University Press, New York.

Lyons, J. 1992. Using the index of biotic integrity (IBI) to measure environmental quality in warmwater streams of Wisconsin. U.S. Forest Service General Tech. Rept. NC-149. 51 pp.

Matthews, W. J. 1988. North American prairie streams as systems for ecological study. Journal of the North American Benthological Society 7:387-409.

Metcalfe-Smith, J. L. 1994. Biological water-quality assessment of rivers: use of macroinvertebrate communities. pp. 144-170, IN: P. Calow and G.E. Petts (eds.) The rivers handbook, vol. 2. Blackwell Scientific Publications, Oxford.

Naiman, R. J., ed. 1992. Watershed management. Balancing sustainability and environmental change. Springer-Verlag, New York.

Naiman, R. J., J. J. Magnuson, D. M. McKnight and J. A. Stanford (eds.). 1995. The freshwater imperative. A research agenda. Island Press, Washington, D.C.

Patrick, R. 1992. Surface water quality: have the laws been successful? Princeton University Press, Princeton.

Poff, N. L. and J. V. Ward. 1990. Physical habitat templet of lotic systems: recovery in the context of historical pattern of spatiotemporal heterogeneity. Environmental Management 14:629-645.

Polls, I. 1994. How people in the regulated community view biological integrity. Journal of the North American Benthological Society 13:598-604.

Propst, D. L. 1982. Warmwater fishes of the Platte River basin, Colorado; distribution, ecology, and community dynamics. Doctoral dissertation. Colorado State Univ., Ft. Collins.

Propst, D. L. and C. A. Carlson. 1986. The distribution and status of warmwater fishes in the Platte River drainage, Colorado. Southwestern Naturalist 31:149-167.

Rapport, D. J. 1989. What constitutes ecosystem health? Perspectives in Biology and Medicine 33:120-132.

Resh, V. H. and J. K. Jackson. 1992. Rapid assessment approaches to biomonitoring using benthic macroinvertebrates. pp. 192-229, IN: D. M. Rosenberg, V. H. Resh (eds.). Freshwater biomonitoring and benthic macroinvertebrates. Chapman and Hall, New York.

Schindler, D. W. 1987. Detecting ecosystem responses to anthropogenic stress. Canadian Journal of Fisheries and Aquatic Science 44:6-25.

Schrader, L. H. 1989. Use of the index of biotic integrity to evaluate the effects of habitat, flow, and water quality on fish communities in three Colorado Front Range rivers. Master's thesis. Colorado State Univ., Ft. Collins.

Schumm, S. A. 1977. The fluvial system. John Wiley & Sons, New York.

Scott, M. L., M. A. Wondzell and G. T. Auble. 1993. Hydrograph characteristics relevant to the establishment and growth of western riparian vegetation. pp. 237-246, IN: H. J. Morel-Seytoux, (ed.). Proceedings of the Thirteenth Annual American Geophysical Union Hydrology Days. Hydrology Days Publications, Atherton, CA.

Silkensen, G. 1993. South Platte River observations: historical clues to the evolution of a river's ecology. pp.41-55, IN: Defining ecological and sociological integrity for the South Platte River Basin. Information Series No.72, Colorado Water Resources Research Institute, Colorado State University, Fort Collins.

Stanford, J. A. and J. V. Ward. 1992. Management of aquatic resources in large catchments: recognizing interactions between ecosystem connectivity and environmental disturbance. pp. 91-124, IN: R. J. Naiman (ed.), Watershed management: balancing sustainability and environmental change. Springer-Verlag, New York.

Stednick, J.D. 1987. The potential of subalpine forest management practices on sediment production. pp. 95-100, IN: Management of Subalpine Forests: building on 50 years of research. USDA Forest Service. Rocky mountain Forest and range Experiment Station, General Technical Report RM-149.

Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell and C. E. Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences 37:130-137.

Ward, J. V. and J. A. Stanford. 1983. The serial discontinuity concept of lotic ecosystems. pp. 29-42, IN: T. D. Fontaine and S. M. Bartell (eds.). Dynamics of lotic ecosystems. Ann Arbor Science Publications, Ann Arbor.

Washington, H. G. 1984. Diversity, biotic and similarity indices: a review with special relevance to aquatic ecosystems. Water Research 18:653-694.

Whittier, T. R. and S. G. Paulsen 1992. The surface waters component of the Environmental Monitoring and Assessment Program (EMAP): an overview. Journal of Aquatic Ecosystem Health 1:119-126.

Winston, M. R., C. M. Taylor and J. Pigg. 1991. Upstream extirpation of four minnow species due to damming of a prairie stream. Trans. Am. Fish. Soc. 120:98-105.

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