An Examination of References for Ecosystems in a Watershed Context: Results of a Scientific Pulse in Redwood National and State Parks, California

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Characteristics of reference sites for stream and riparian ecosystems were examined and discussed during a 'pulse' (a short, interdisciplinary field-based inquiry) that visited three pristine streams in old-growth redwood forests in northern California. We concluded that useful reference sites need not be pristine, but must be rich in data linking physical and biological processes, and must frame conditions in a watershed context. Not requiring pristine conditions allows data-rich watersheds with a spectrum of conditions to be incorporated into a regional reference framework. We describe and exemplify three types of references: 1) Reference sites (e.g., watersheds) offer real-world examples of how ecosystems function over time; 2) Reference parameters measured in a region offer first-cut comparisons that can lead to deeper, more contextual analyses; 3) Analytical references can reveal disturbance-related departures from conditions predicted with simple assumptions about some aspects of system behavior. Each type has strengths and weaknesses, and used in combination they can effectively inform management decisions.

Keywords: *environmental references, stream ecology, fluvial geomorphology, watersheds*

Introduction

Ecosystem management requires interdisciplinary problem solving and an expanded scale and scope of analysis, particularly in lotic and riparian ecosystems that are integrated by the flux of water, sediment, organic material, organisms, heat, and dissolved constituents through watersheds. The need to address interactions between physical and biological processes over the landscape is perhaps greatest at the scale and organization of a watershed, where each point responds to cascading influences from upstream, upslope, and upwind over a range of time scales. Now, with the growing appreciation that biological functions are embedded in physically dynamic landforms (e.g., Minshall 1988; Fausch et al. 2002; Benda et al. 2004), the underlying problem for land managers is, how do physical and biological processes interact in a watershed, or, how does a living watershed function? With incomplete information about these complex systems, resource professionals commonly seek references to serve as benchmarks of functioning systems, asking 'What does a properly functioning watershed look like?'

Managers, regulators, and scientists commonly use relatively pristine systems as references against which to compare other sites of the same type or region that have comparable management issues (USGS 2004). Conditions are evaluated by comparing data for a set of quantitative parameters from pristine and managed systems. The assumption is that human effects account for significant departures from reference conditions and can be analytically separated from variations due to climatic events (e.g., hurricanes) or state variables (e.g., geology, topography), which are assumed to affect the site independently of human influence.

References other than pristine systems are available in the land-management arena, as suggested by Webster's broad definition of reference, '…taken or laid down as standard for measuring, reckoning, or constructing'. Nevertheless, reference conditions are usually associated with pristine or desired states – the "best" sites a region has to offer. In some

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cases "reference condition" is defined based on a specific reference site and becomes the target for restoration efforts, and later, for the evaluation of restoration effectiveness (Jungwirth et al. 2002; SER 2002). For example, a 'desired future condition' can be based on some perceived pristine or near-pristine condition that enhances a valued resource, e.g., productive fish habitat, without being tied to specific reference sites (Salwasser et al. 1996).

Any use of reference conditions should include an analysis of spatial and temporal variability. 'Historic range of variability' (Landres et al. 1999) describes the variability of ecological conditions particularly in the period before and after European settlement in North America. The concept that ecosystems are disturbed and recover from natural occurrences such as floods (Wolman and Gerson 1978), volcanic eruptions (Franklin et al. 1995) and wildfire (Minshall et al. 1997) emphasizes that all systems are in some stage of evolution from major events (Reeves et al. 1995).

Scale is a primary consideration in spatial variation. In some areas of the United States, ecoregions (Omernik 1987) have been divided into sub-regions as a framework for establishing ecological expectations – reference conditions – that are based on the sampling of many minimally impaired reference sites within the sub-region (Ohio EPA 1987). Physical, chemical, and biological data have been used to establish a database of reference conditions for the sub-region. In some cases, a reference framework is based on statistical analysis of a set of sites interpreted to represent reference conditions (e.g., Clarke et al. 2003). Ordination and principal component analyses have also been used to establish reference sites from large regional data sets. However, qualitative "best professional judgment" criteria are still used to select from the array of data the sites that should serve as references (e.g., McIninch and Garman 2002). Comparisons of such reference sites with those judged to be impaired encounter statistical problems of pseudo-replication (Stewart-Oaten et al. 1986) and fail to account for the inherent succession of ecosystems (Loehle and Smith 1990)

These considerations lead to the question, 'Is there something inherent in the reference sites, perhaps complexity or diversity, that sets them apart from others across regions regardless of temporal variability?' To examine this problem, a pulse study conducted by multi-disciplinary teams was held in the old-growth redwood forests of Redwood National and State Parks (RNSP) in north coastal California in June, 2003. Discussions during and following the Redwood Pulse resulted in a re-evaluation of, and some new proposals for, the use of various forms of references in the management of watershed ecosystems.

The Redwood Pulse

The Redwood Pulse was modeled after the procedure established by Dr. Jerry Franklin (USDA Forest Service, Pacific Northwest Research Station, now at University of Washington), whereby multi-disciplinary teams of scientists focus their collective wisdom and insights on ecosystem functions at a specific site during short, field-based inquiries (Franklin 1982). Hence the term pulse.

The goal was to arrive at new insights about linked aquatic-terrestrial ecosystems. In the leadup to the Redwood Pulse, a framework for inquiry was developed concerning the notion of 'reference condition' as applied in watershed studies. The discussions centered on the importance of natural variability in the parameters selected to characterize a site, whether at the reach or the watershed scale. A collective interpretation was that this variability gives those sites less modified by human activities much of their resilience to natural disturbance. In this view, parameters in pristine sites could exhibit high variance at any point in time, and human disturbance could lead to a reduction in variance. As a consequence, reference sites might actually be more variable than disturbed ones. Thus, the motivating question for the Redwood Pulse was, 'Would reference sites, here defined as most-pristine, exhibit more variation in selected parameters than would be expected in disturbed sites in the same region?' This relative variability was anticipated to be distinguishable to the attendees who collectively had wide-ranging field experience in the Redwood and similar regions.

The pulse participants represented a range of disciplines, including geomorphology, hydrology, fisheries biology, aquatic ecology, plant ecology, entomology, social science, soil science, and natural resources management. (A list of participants is available on request from the corresponding author.) We did not visit disturbed sites nor collect data with the intention of testing an hypothesis. Instead, we used the question of ecosystem variability as a springboard to discuss reference concepts in a field setting. During the pulse, teams from the larger group of twenty-one participants worked side by side, focusing their particular expertise on each site in turn and continuously exchanging perspectives as they made observations and some measurements. During the evening, these separate insights were discussed, integrated, and recorded around the campfire in the Franklin tradition.

In this paper, we report the results of the discussions and propose that the richness of data on influential abiotic and biotic processes can qualify a site as an ecosystem reference, in addition to its condition. Our initial focus on variability led to a conclusion that data richness is an important criterion for selecting reference sites. We also

Table 1. Characteristics of pulse sites.

	Site 1: Upper Prairie Creek	Site 2: Godwood Creek	Site 3: Little Lost Man Creek
Watershed area (km^2)	10.5	4.0	9.9
Stream gradient (%)	1.0	1.6	2.6
Bedrock geology	Coastal plain sediments	Coastal plain sediments	Sandstone and mudstone
Dominant riparian overstory	Old-growth redwood on floodplain	Old-growth redwood on banks	Old-growth redwood high on banks
Sub-dominant riparian composition	Red alder and big leaf maple[1]	Hemlock, spruce, vine maple, alder[3]	Red alder near edge of stream, big leaf maple
Percent canopy cover	80	85	80
Bankfull width (m)	7	5	8
Valley width (m)	130	83	40
Bed surface grain size: D_{50} (mm), *S.D.* (phi scale)	67 (*1.1*)	18 (*1.3*)	54 (*2.1*)
Dissolved oxygen	94.7%	97.1%	97.3%
pH	6.65	7.36	7.37
Conductivity (µs/cm)	61.7	90.3	52.6
Trophic status	Highly autotrophic	Slightly autotrophic	Highly heterotrophic
Salmonids	coho, Chinook, steelhead, cutthroat[2]	Same	Same

[1] **Red alder, *Alnus rubra*; big leaf maple, *Acer macrophyllum*.**
[2] **Coho salmon, *Oncorhynchus kisutch*; Chinook salmon, *O. tshawytscha*; steelhead, anadromous *O. mykiss*; cutthroat trout, *O. clarkii***
[3] **Vine maple, *Acer circinatum***

compare the utility of reference sites with two other types of reference: reference parameters and analytical references.

Observations and Discussions

Table 1 lists some characteristics of the three stream reaches visited during the pulse, all within the Prairie Creek basin and judged to be "pristine" by Park personnel and scientists from local agencies and universities. Their basins are uncut except for Little Lost Man Creek, which contains a 35-year-old, 40-acre patch cut, and Upper Prairie Creek, which is crossed by a paved road. The Yurok people located their villages outside these deep woods and the occasional understory fires that they would light did not harm the large redwood trees (*Sequoia sempervirens*) (Sawyer et al. 2000) Although all three streams flow through old-growth redwood forests with an understory dominated by ferns and salmonberry (*Rubus spectabilis*), the influence of the redwood trees on the stream differed according to the height and width of the floodplain and the proximity of the trees to the channel (Figures 1, 2 and 3). Godwood and Upper Prairie Creeks are underlain by poorly indurated gravel and sand considered to be deposits of an ancestral Klamath River of Plio-Pleistocene age (Kelsey and Trexler 1989). As a consequence, some of the modern bed particles may have been transported and sorted under very different hydraulic conditions than are present today, but the modern channels are apparently adjusted to transport this imposed particle-size distribution. Little Lost Man Creek is underlain by a more competent sandstone unit of the Francisican Assemblage (Cretaceous age) including coherent sandstone with some interbedded sandstones and mudstones. This stream reach was steeper and more confined than the other two.

Although all three sites were considered pristine, participants observed strong differences between them, including species composition of the riparian zone, proximity of old-growth redwoods to the stream channel, abundance of fine sediment, patchiness of light reaching the stream bed, distribution of riffles and pools, and location and size of large wood within the channel and on the streambanks and floodplains. Most notably, the riparian stand characteristics were very different. The pristine site in Little Lost Man Creek exhibited sediment effects that are usually attributed to human disturbance, such as unstable banks, high bed mobility, and a drape of silt over the gravel armor.

The instream biology was correspondingly variable. For example, invertebrate samples indicated that the Upper Prairie and Godwood Creek sites were autotrophic (food sources produced instream), with the former much more so than the latter, while Little Lost Man Creek was strongly heterotrophic (food sources contributed by the riparian area) (e.g., Merritt et al. 2002). All three stream sites exhibited algal development, including some filamentous forms, associated with light gaps. The ratio of invertebrates

*Figure 1. (Above) Site 1 is Upper Prairie Creek (photographed March 2004). At Upper Prairie Creek, alders (*Alnus rubra*) grow close to the channel (foreground), maples (*Acer *spp.) are found on a 1- to 2-m-high floodplain, and old-growth redwoods grow on a higher terrace about 2 m high (in background). Although the stream drains an old-growth redwood forest, hardwoods and shrubs rather than redwoods influence the channel directly in terms of litterfall, shade and wood. This led to a high 'patchiness' of sunlight reaching the stream channel, and low levels of large in-channel wood (although numerous redwood snags and large down wood exist on the floodplain). The wide floodplain in this area supported an abundance of small back channels, high flow channels and alcoves. Banks were composed of coarse cobbles and boulders derived from ancient Klamath River deposits, so the streambed particles were, in a sense, pre-washed, pre-rounded and deposited under different hydraulic conditions. The channel has well developed gravel bars.*

that use periphyton (scrapers) relative to those that use detritus (shredders + collectors) as a food source was used to evaluate autotrophy versus heterotrophy at the stream ecosystem level. The discrepancy between the high penetration of light to the stream bed in Little Lost Man Creek and the very low density of periphyton scrapers was likely due to dense growths of filamentous algae on coarse substrate surfaces. Scrapers are not able to feed efficiently on filamentous algae (Cummins and Klug 1979).

The three sites also differed significantly in abundance of invertebrates that filter fine particulate organic matter (FPOM) in transport (organic portion of suspended load) as their food source and require abundant stable substrates for attachment. Upper Prairie and Godwood Creeks apparently had plenty of stable substrates (large cobbles) but a poor supply of appropriate FPOM for filtering collector food supply. Water clarity at all three sites indicates little suspended load, and the lack of filtering collectors likely further reflects a poor supply of FPOM in suspension. Little Lost Man invertebrates indicate a lack of sufficient stable substrates as well as a poor FPOM supply. Much of the cobble substrate was covered with filamentous algae, which likely rendered their surfaces unsuitable for attachment by filtering collectors or grazing by algal scrapers.

*Figure 2. Site 2 is Godwood Creek. (photographed March 2004). Godwood Creek has more cohesive banks than the other sites, so undercut banks and overhangs are common. At this site, redwoods grow on the edge of the banks and channel, most commonly on terraces 2 to 3 m high. Spruce (*Picea sitchensis*) and hemlock (*Tsuga heterophylla*) are also components of the conifer overstory at this site. Vine maples (*Acer circinatum*) overhang the channel in many areas, but alders are not prevalent. This site is the shadiest of the three, with little algae in the stream. Large in-channel wood is abundant, and many point bars and log jam deposits are present in this reach. The channel substrate consists of loosely packed pebbles and small cobbles.*

Figure 3. Site 3 is Little Lost Man Creek (photographed March 2004). Little Lost Man Creek has the coarsest substrate of the three sites, with some 1-m diameter boulders in mid-channel. The floodplain is narrow and point bars are infrequent. Several instances of recent bank failures were noted. Fern-covered streambanks are steep and are devoid of large trees on the lower 7 to 8 m (perhaps indicative of a past debris torrent disturbing the channel banks). However, when trees fall, they commonly reach the stream and large in-channel wood was more abundant here than in Upper Prairie Creek. Alders grow at the channel's edge. Filamentous algae were present during the July visit.

Our data collection exercises motivated discussions of stream reach variability and reference conditions. A related and recurring question that arose while visiting the sites was, 'How did the site get this way?' (again, in the Franklin tradition). We agreed that a knowledge of the legacy of a site, in terms of long-term state variables (e.g., climate and geology) and the disturbance history (e.g., floods, fires, and landslides), was critical to understanding current conditions and ecosystem processes. This reinforces the conclusion that a key requirement of a reference site is the extent of available data, regardless of where the site might lie along a spectrum from pristine to disturbed.

Types of Reference

The original question of the characteristics of pristine reference sites evolved into an examination of the types of references (Table 2) and their usefulness in evaluating the condition of aquatic and riparian ecosystems in the context of their watersheds.

Reference parameters. Perhaps the most widely used referencing approach is to directly compare the value of a parameter measured at a site of interest to a reference value, range, or distribution, without considering influencing processes. References can be derived from sites judged to be pristine or representative, or from sites sampled randomly in a region. A single-valued reference parameter can take the form of a sample statistic (e.g., mean, maximum or minimum), a scientifically determined or regulatory threshold leading to a degraded condition, or a desired state. A single-valued reference leaves no ambiguity as to whether a criterion is met, but the variability of natural systems suggests that such a comparison is too simplistic.

Table 2. Reference types; their expressions as values, models or locations; and examples.

Reference Type	Expression	Example
Parameter:		
Single value	Average	Pools per mile
	Minimum, maximum	Water temperature
	Threshold	Total Maximum Daily Load (USEPA)
	Presence /absence	EPT [Ephemeroptera (mayflies), Plecoptera (stoneflies), Coleoptera (caddisflies)]
Distribution	Range	Flow regime?
	Cumulative percent	Wood volume/channel area
Process	Value or distribution	Litter input/area-year
Analytical reference		
	Budget	Water, sediment, sediment, dissolved constituents, temperature
	Distributed models	SHALSTAB (Dietrich and Montgomery 1998).
Site:		
Watershed	Reference watershed	H.J. Andrews (LTER), Caspar Creek Experimental Watersheds
	Reference framework	National Ecological Observatory Network (proposed)

Even if used merely as a benchmark, it does not provide an interpretation of a deviation from the reference value unless, as a threshold, it triggers some regulatory action.

A comparison against the full distribution of values from a set of data offers a broader use of reference parameters. Here, the distribution of values from a set of reference sites is presented as a range, standard deviation, or cumulative frequency distribution. Comparison of values against the reference distribution provides information on the deviation from the central tendencies of the reference sites. This broader approach is more informative and can reveal the uncertainty in making management decisions. Distributions of environmental parameters (e.g., wood loading, sediment concentrations) measured in managed and pristine systems in the same region commonly overlap (Lisle 2002). Commonly the 'best' reference sites exhibit wide variation in the parameters selected as measures of their condition, making it difficult to define a target for restoration.

A reference can represent a level of achievement of acceptable conditions on a scale that runs from 'not properly functioning' or 'at risk', to 'properly functioning' (NMFS 1996, 1999). However, a reference condition does not need to represent a pristine system or a target, but can be a benchmark for comparison without a predetermined value or decision context. Application of the Webster definition is still appropriate – a standard to compare with a system in order to help guide analyses to better understand how it got this way and what its trajectory is. Nevertheless, a useful reference must contain some meaning in order to allow an interpretation. In this view, a reference can be used to expose extraordinary conditions and be used in the analysis of cause and effect (e.g., stream cleaning, recent debris flow, influences on riparian communities).

However, any reference parameter is limited in its usefulness to understanding causal linkages, and expanding the scale and context of a reference demands new strategies. One strategy is to quantify relations between terrestrial riparian and aquatic conditions by focusing on processes that transfer watershed products between parts of the watershed ecosystem. Because physical and ecological processes occur at a variety of time scales, a meaningful reference for a parameter like wood loading could be the annual or decadal inputs of wood that are governed by rates of mortality from disease, windthrow, bank erosion and landslides and, ultimately, tree growth (Van Sickle and Gregory 1990; Benda et al. 2002). Also, reference processes could include seasonal or annual rates of primary production or nutrient cycling or fluxes of sediment, nutrients, or organisms. A reference could be used to track trends in processes over time at the same site in the same watershed, or to compare processes among different sites or watersheds in a region. Concentrating on rates of movement from one state to another provides insight into the mechanisms resulting in variability in space over time. For example, with regard to invertebrate life cycles, all three of the sites examined in the Redwood Pulse were dominated by those taxa with annual or shorter generation times. These would be populations with the potential for quick response to changes in the physical environment, and their presence is not very compatible with a view of pristine systems as being relatively stable.

Analytical references. Expanding the use of references from reaches to watersheds requires more than just expanding the same site-scale measurements to more places. One strategy is to employ an analytical reference such as a budget, that is, a statement of spatial and temporal variations in inputs and outputs and changes in storage of a watershed product such as sediment (Reid and Dunne 1996), wood (Benda and Sias 2003; Hassan et al. in press), or particulate organic matter.

As an example, inputs of particulate organic matter (POM) were generally in balance with outputs for a small first-order woodland stream in Michigan (Figure 4) as well as for twenty-three reaches in four different watersheds (Figure 5). The amount of detritus in storage in a reach of stream is the result of biological activity (microbial respiration, invertebrate assimilation) and flow-related loading and unloading of storage in the sediments. The majority of the POM is stored in fine particles, which account for the majority of microbial respiration and 80% of the invertebrate assimilation (Petersen et al. 1989).

In the case of large woody debris (LWD), although historic values for volumes lost or gained usually cannot be determined precisely, enough can be learned of past events and conditions to roughly evaluate departures from natural loadings. This allows some basic questions to be addressed:

- What accounts for present wood loading, and more specifically, how much has land use affected riparian sources and input and output mechanisms?
- What is the trajectory in wood loading given the present and future potential of the riparian forest to contribute wood to the stream?
- Which management alternatives are consistent with the desired trajectory?

Another form of analytical reference is the output of a numerical model relating an environmental or ecological variable to a simplified representation of one or more watershed processes that is applied to the conditions and state variables of a target watershed (Power et al. 1998). Thus, the primary purpose of an analytical reference is not to accurately predict actual conditions, but to project what

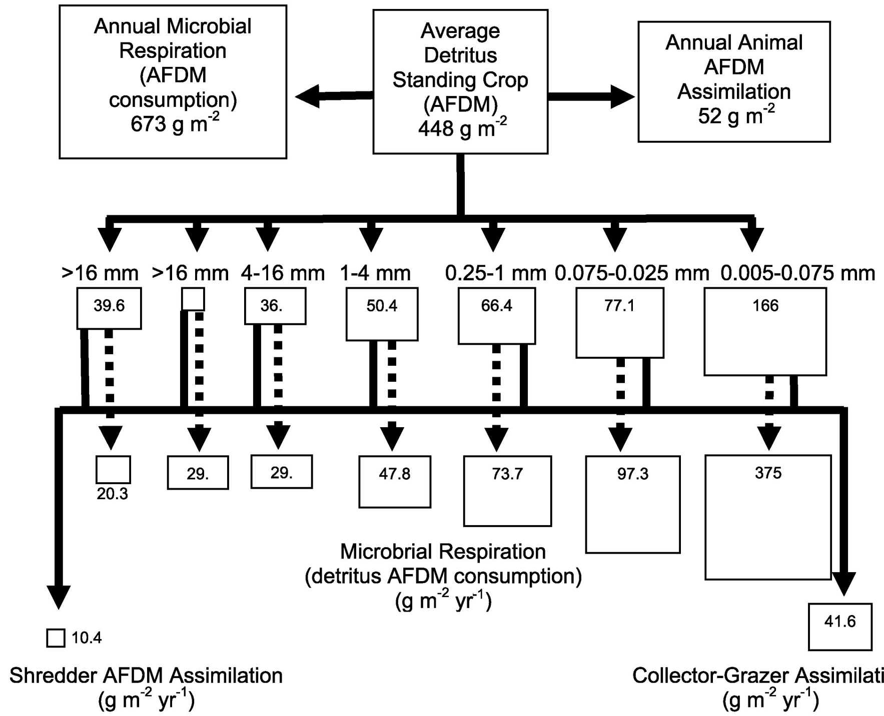


Figure 4. Summary of annual average ash free dry mass (AFDM) in the benthic detritus (bedload) standing crop and consumption by microbial respiration and animal assimilation. Microbial respiration (hatched arrows) and invertebrate (shredders, collectors, and scrapers) assimilation (open arrows) apportioned by mm particle size categories (16 mm W = wood, bark, twigs – a very resistant fraction; 16 mm L = leaf litter). All particle sizes > 1 mm are defined as coarse particulate organic matter (CPOM) and < 1 mm defined as fine particulate organic matter (FPOM). Data from a first order tributary of Augusta Creek in southern Michigan. Modified from Petersen et al. (1989).

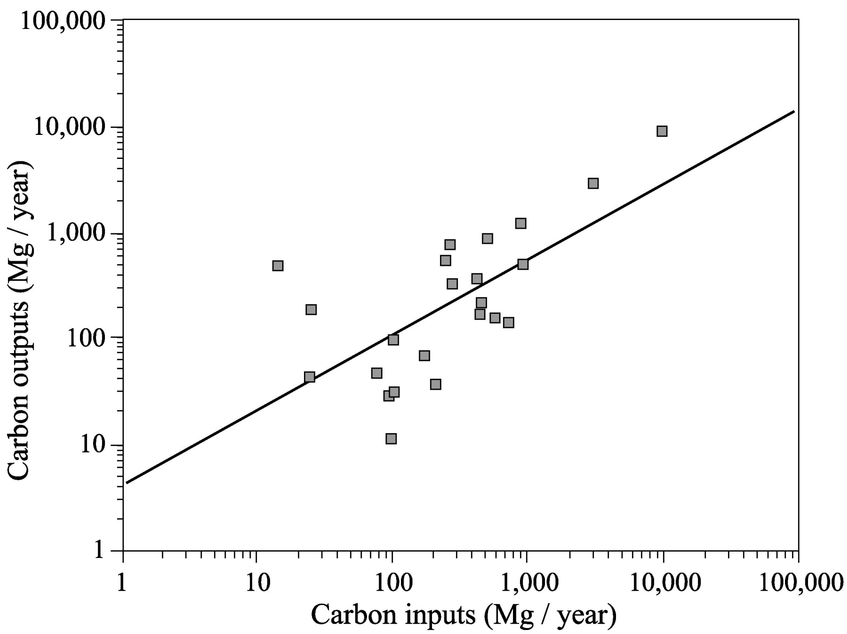


Figure 5. Generally balanced relationship between annual carbon inputs and outputs for 23 stream locations in four watersheds. Modified from Petersen et al. (1989) and based on data in Cummins et al. (1983).

would be found if certain assumptions or conditions were met. Deviations from the analytical reference can reveal the relative strength of other influences.

For example, reference particle sizes of sediment on streambed surfaces in a watershed can be computed from drainage area and channel slope of each reach by assuming that a gravel bed should be at the threshold of movement under bankfull discharge conditions (Power et al. 1998). This is a characteristic of active gravel-bed channels that maintain equilibrium with modest sediment loads. A streambed that is much coarser than the reference particle size could indicate sediment starvation or inputs of large material by debris flows or landslides; a much finer bed could indicate large channel-routed sediment loads, particularly of fine material.

Similar theoretically based models are available for referencing stream temperature based on shade (Bartholow 2002), woody debris loading based on topography and riparian stand structure (Van Sickle and Gregory 1990), the occurrence of shallow landslides based on drainage area and slope [SHALSTAB (Dietrich and Montgomery 1998)], and invertebrate communities dependent on the predictable nature of riparian litter inputs (Grubbs and Cummins 1996).

Numerical models provide a site-specific, theoretical framework to examine relations between environmental conditions and controlling processes. They also enable simulations based on a wide range of scenarios and tests of ecosystem sensitivity to stressors. However, the power of numerical models is limited by the very strategy that makes them computationally possible-simplification of the whole suite of processes that determine the functions of ecosystems in the context of their watersheds. In fact, every model can do no more than produce a reference, because none can incorporate all of the conditions and processes that govern the behavior of a natural system.

Reference watersheds. There is a commonly held view that human influences on watershed conditions transcend those due to climatic events or state variables, thus significant departures from reference values within the same region must be due to human activities. Our observations in the Redwood Pulse led us to doubt that view. We found, for example, that geology in a pristine site we examined produced channel conditions that are commonly attributed to human disturbance. It was clear that establishing a local context – 'how it got that way' – is essential to applying a reference approach.

To this end, we conclude that expanding both the context and scale of references would require a database linking processes in an integrated system – a reference watershed. We envision reference watersheds as real-world examples of the full suite of processes that govern the functioning of a living watershed. Watersheds could qualify as references by having comprehensive, long-term data bases. Our vision of reference watersheds is most closely represented in Long Term Ecological Research (LTER) sites and experimental watersheds that are devoted to research and protected from endemic land use, except for controlled experimental treatments. Many, but not all, LTER sites are essentially pristine. Thus our view that data richness, rather than condition, is a primary requirement conforms to an existing system of reference watersheds. Insofar as pristine watersheds in many regions are rare, this expands the number of watersheds that could be used as references.

A reference watershed should be large enough (say, 10^0-10^1 km^2) to incorporate important processes linking terrestrial, riparian, and aquatic ecosystems in a network of low-order tributaries. They should be rich enough in data and information to explain the variability in observed environmental parameters and their relation to causal factors (again, "how it got this way"). Although it is important to know how pristine systems work, it is also important to know how cumulative effects occur in disturbed systems and what impacts to monitor. Moreover, both pristine and anthropogenically disturbed watersheds are subject to infrequent large disturbances such as wildfire and floods, and thus a variety of states can exist within and among any number of reference watersheds. Examples of data-rich reference watersheds include LTER sites [including H.J. Andrews, in Oregon (*www.fsl.orst.edu/lterhome.html*); Hubbard Brook, in New Hampshire (*www.hubbardbrook.org*); Coweeta, in North Carolina (*coweeta.ecology.uga.edu/webdocs/1/index.htm*)], many of which were once treated experimentally but are now off-limits to major treatments. Others include watersheds associated with Biological Field Stations. For example, Augusta Creek at the Michigan State University Kellogg Biological Station (Mahan and Cummins 1978) or Linesville Creek at the University of Pittsburgh Pymatuning Laboratory of Ecology (Coffman et al. 1971), and experimental watersheds [e.g., Caspar Creek, northern California (*www.fs.fed.us/psw/topics/water/caspar/*)] that still undergo periodic large-scale treatments.

Ideally, the number of reference watersheds could be expanded to include a wider range of conditions. This would allow conditions in a targeted watershed to be compared to those resulting from a range of disturbance intensities (natural or anthropogenic) and state variables. With extensive data, the causal linkages would be relatively well known in the reference watersheds. Comparisons between watersheds would reveal not only the departure of environmental variables from desirable states, but also the linkages that would suggest how more desirable conditions could be achieved. Moreover, reference watersheds could aid analyses of target watersheds by revealing the strong pathways between watershed condition and environmental variables. Depending on the condition of the target watershed, some reference watersheds may be more useful than others. Reference watersheds in a similar condition could indicate how the target watershed functions now, whereas more pristine references could indicate how it might function in an improved condition, and therefore suggest the most plausible approach to restoration. A broader reference framework would evolve as watersheds that host research or administrative studies accumulate enough data to assume the role of a reference watershed. This could occur naturally as analyses prompted by initial comparisons with the 'founding' reference watersheds expand the information base for other watersheds. Recently developed remote sensing and analytical techniques (LIDAR, GIS) enable rapid accumulation of large-scale data sets for new areas.

Relative utility of reference types. The three types of references vary in the degree to which they address a number of issues important to analysis of watershed ecosystems (Figure 6):

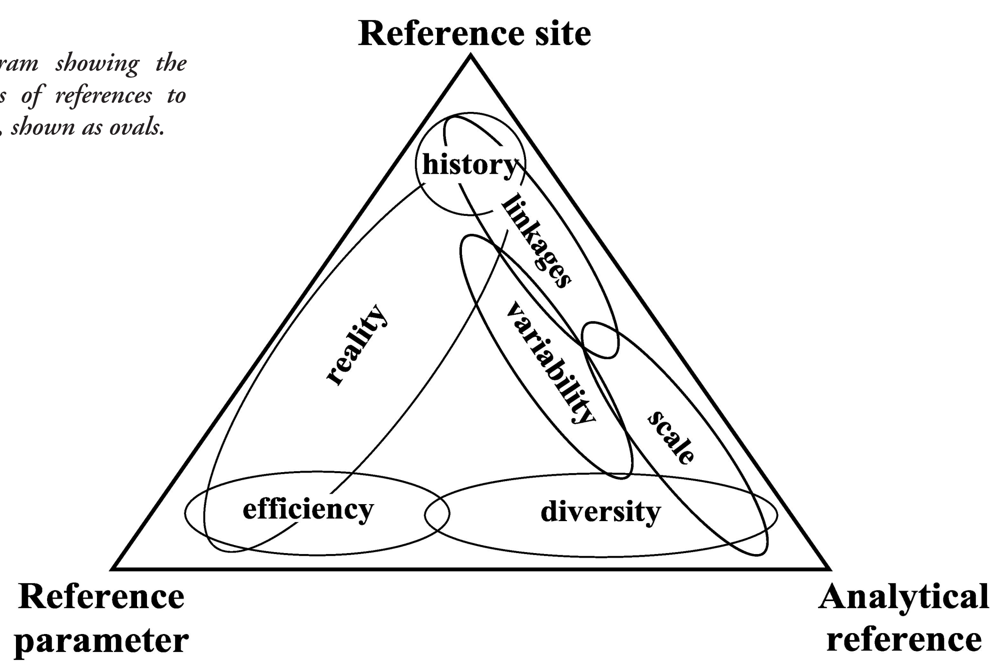
- **Linkages** – A reference should incorporate linkages between processes that determine ecological conditions in order to enable analyses of cause and effect. The complexity of natural systems characterized by cascading fluxes of watershed products through various landforms requires a broad scope of analysis. The capacity to link aquatic biota to the stochasticity of the physical system (such as matching critical life history stages with hydrology and temperature) is a valuable attribute of a reference.
- **Scale** – For many problems, the spatial scale of analysis needs to embrace geographic areas (watersheds) that influence a reach of river, and time periods, that cover major climatic fluctuations (e.g., ENSO).
- **Temporal variability** – Sequences of events and contingencies create a wide range of possible outcomes in natural systems that are conditioned by past events and climatic change.
- **Diversity** – To separate anthropogenic effects on ecosystems, references must address the wide diversity in underlying controls, such as landforms, climate, and geology, that affect ecological conditions and processes in a region.
- **Efficiency** – All of the preceding present complications for arriving at an assessment of the effects and risks of ecosystem management. Nevertheless, references must be understandable and practical for use by managers.
- **Reality** – The real world is the ultimate reference, and references must represent it as accurately as possible.
- **History** – Conditions in watershed ecosystems are the culmination of environmental events and processes played out over time and space. Knowledge of history at local and regional scales provides the background to project reference conditions backward and forward, so that contemporary conditions can be interpreted in the context of environmental trajectories.

Reference sites, such as LTER sites or experimental watersheds, ground us in the functioning of real watershed ecosystems over time. The linkages are there to discover and quantify, although there are technological and institutional limitations on the scope and scale of information that can be gathered. The value of reference sites increases exponentially as records lengthen and the systems become more completely understood. Analyses that employ this information can become more powerful by using data from reference watersheds in other areas that have different controlling conditions, or from less data-rich watersheds in the same region, as described earlier as a reference framework. However, reference sites are limited in their capacity to reveal variability, because they represent one history of an infinite number of possibilities created by climatic variability and disturbance events.

Reference parameters provide real-world information at a regional scale and are often readily available. They provide straightforward comparisons with monitoring data, revealing anomalies and prompting more in-depth analyses. However, without further analysis, interpretations are severely limited because of lack of context with other conditions and processes that lead to cause and effect.

Analytical references are becoming more attractive as references because they can address a wide range of scales,

Figure 6. Triangle field diagram showing the relative capacity of three types of references to provide qualities of information, shown as ovals.



stochastic processes, and levels of risk. They explicitly make linkages between various processes and conditions, and can simulate events that have not been observed. In the final analysis, however, they are only as good as their representation of reality, which must be confirmed by examination of real places in real time.

Conclusions

Redwood Pulse participants examined the nature of conditions of three pristine channel reaches that would commonly serve as references. The resulting discussions led to a reappraisal of what constitutes a valuable reference and an appreciation of the utility and shortcomings of a broad range of reference types.

We concluded that a reference site should be a well-studied system, not necessarily pristine, but rich in data linking watershed and ecological processes. For managers, the great benefit of this approach is that pristine watersheds may not be required to establish workable management goals. A greater emphasis on gathering and integrating significant data sets through time would expand the number of watersheds that could be used to establish references. This opens the possibility of formulating a regional referencing framework whereby data-rich watersheds with a spectrum of conditions provide a context for investigating cumulative effects.

A referencing framework provides a means to determine the causal linkages between underlying conditions, environmental variation, and the functioning of the watershed and its ecosystems. In comparison, stand-alone reference parameters taken out of context of the variety of settings where they are measured or applied offer limited interpretive power. Nevertheless, such parameters are easily available and allow initial comparisons that should motivate deeper analyses. Moreover, the full set of values of a particular parameter in a region offers a wider context for interpretation than a single value, such as a threshold or average. Reference parameters that express process or function, that is, rates rather than state variables, are more likely to capture linkages influencing ecosystem condition.

Analytical models provide formal, explicit organization of our understanding of these interactions and a means to sort out strong influences from weak ones, and anthropogenic effects from natural ones. As analytical tools are developed with new knowledge and techniques, analytical references will provide a new wave of approaches for addressing cumulative watershed effects. However, models are ultimately based on knowledge and data from real systems, and their development should motivate new, interdisciplinary field studies.

Finally, Pulse participants concluded that references are essential tools in management-driven analyses of watershed ecosystems, where biological and physical processes interact in a complex structure of linkages activated by stochastic disturbances. Our discussions revealed a variety of reference types, each with strengths and weaknesses, which can be integrated to support more effective, full-scale analyses. Science-based management decisions will always rely on incomplete understanding of watershed ecosystems, but analyses using data-rich reference sites and valid analytical models, combined with the best professional judgment, will help to achieve the competing goals of the public's interest in resource management.

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