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# The Use of Reference Ecosystems as a Basis for Assessing Restoration Benefits

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**OVERVIEW:** The use of type-specific reference conditions can significantly improve planning, implementation, and monitoring of ecosystem restoration projects. Effective forecasting of restoration effects on aquatic ecosystems requires an understanding of the structure and function of the system; natural reference systems within a geographical region contribute significantly to this understanding (Griffin et al. 1994). Historically, reference conditions have primarily been applied within the U.S. Army Corps of Engineers (USACE) to identify target functions as an integral part of compensatory mitigation requirements of the Clean Water Act of 1977 (USACE 2011). There has also been some limited application to objective setting and design for ecosystem restoration. In recent years, the importance of reference conditions to a suite of applications has been acknowledged by the scientific community (Miller et al. 2012). However, despite the abundance of guidance related to stream and wetland functions assessment, the criteria used to identify reference conditions and reference approaches have not been adequately addressed across all aquatic ecosystem types. Establishment of reference sites is paramount to assessing wetland functions using the hydrogeomorphic function assessment (Smith et. al. 1995). However, reference sites have not thus far been utilized as a basis for quantifying environmental benefits across aquatic ecosystems. Moreover, reference conditions concepts have not thus far been utilized as a basis for quantifying environmental benefits, despite several potential advantages relative to other options.

The objectives of this technical note are three-fold: 1) to propose uses of reference conditions as a basis for identifying metrics and assessing restoration benefits; 2) to introduce a systemized process to facilitate the selection of suitable reference approaches; and 3) to propose the development of a reference condition index (RCI) that could serve to guide the application of reference concepts to environmental benefits assessment.

The intended audience of this technical note is USACE planners, Headquarters USACE policy makers, model developers, and others with limited knowledge of environmental benefits analysis (EBA). This technical note should be used as a companion to "Reference Concepts in Ecosystem Restoration and EBA: Principles and Practices" (Miller et al. 2012), and the broader "A Framework for Science-Based Environmental Benefits Assessment" (Fischenich et al. 2013).

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The foundation for reference conditions concepts, including five approaches for establishing reference conditions, is presented in Miller et al. (2012).

**BACKGROUND:** The reference condition is the set of attribute values or quantifiable characteristics of the reference ecosystem (Miller et al. 2012). The reference condition provides a contextual background against which the degree of degradation, range of condition, and benefits of restoration can be measured. The reference condition for restoration design has traditionally been associated with ecosystems that are undisturbed by humans (Hughes et al. 1986; Bailey et al. 2004; Society for Ecological Restoration International Science and Policy Working Group (SERI) 2004). However, the term has evolved to include a variety of different meanings (Miller et al. (2012), see Table 1). This evolution reflects the fact that for many restoration projects, undisturbed reference ecosystems do not exist due to changes in land use, development, and hydrologic alterations (Benke 1990, Malmqvist and Rundle 2002). In these situations, the reference condition has often been redefined to reflect the range of values that ecosystem attributes exhibit in the least disturbed ecosystems in the reference domain. In other cases, the reference condition is represented by historical data collected prior to disturbance, or a combination of modeled data and field data to construct a virtual reference. As a result, the reference condition in the ecosystem restoration framework has become a relative term that only has specific meaning in the restoration project context (Miller et al. 2012).

Stoddard et al. (2006) identified several categories of the reference condition used in the context of biological assessment, a number of which are equally applicable to ecosystem restoration. An extension of Stoddard to ecosystem restoration application was included in Miller et al. (2012). Their objective was to establish clarity and standardization by proposing specific terms to represent specific types of reference conditions. Figure 1 conceptualizes the temporal relationship between the various categories of the reference condition. Historical trajectory is depicted inside the bubbles, which represent the various categories of the reference condition indicating variability of ecosystem attributes across space and time. Dashed lines in Figure 1 indicate: (1) continued degradation due to an increasing level of disturbance or stress, (2) continuation of the current conditions, and (3and 4) restoration trajectories leading to alternative meta-stable states (Hobbs and Norton 1996, Yates and Hobbs 1997, Cortina et al. 2006). To enable ecosystem restoration designers to make the best use of reference concepts and determine future ecological states, Miller et al. (2012) outlined five reference approaches for ecosystem restoration (Table 2 of reference). These approaches and the reference conditions (Table 1 of reference) that support them form the framework of discussion for application of the reference condition to environmental benefits analysis.

## APPLICATION OF REFERENCE CONCEPTS TO ENVIRONMENTAL BENEFITS ANALYSIS (EBA):

**Traditional EBA approach.** At a broad level, EBA, as utilized by the Corps, consists of four general phases: 1) a qualitative characterization of the ecosystem, development of the problem statement, and identification of objectives and constraints; 2) development of certifiable assessment methodologies, quantification of future ecological states, assignment of values to changes in ecological conditions, and assessment of associated costs and uncertainties; 3) decision making based on assessing outputs relative to project objectives, costs, and constraints; and

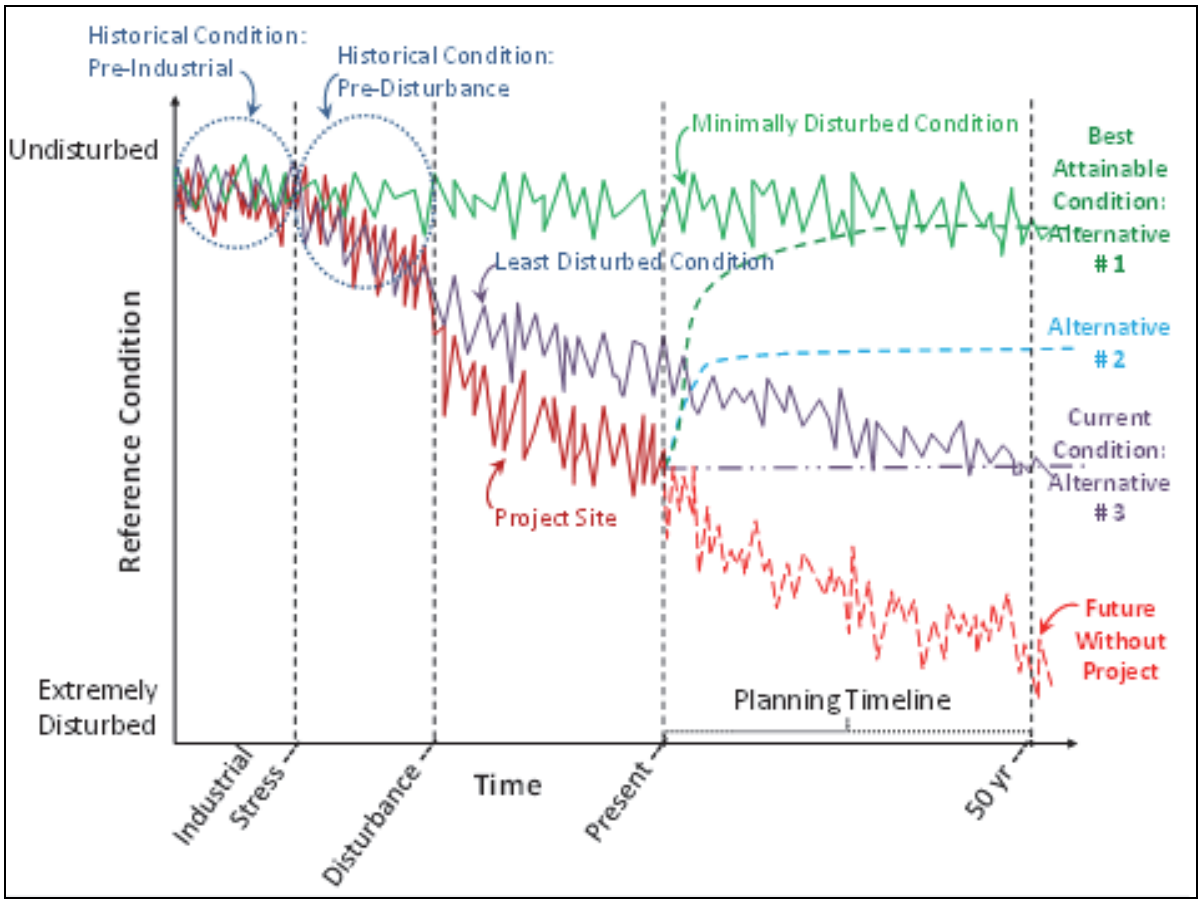


Figure 1. Reference condition types and three project plan alternatives shown with time. All reference types used for design incorporate the trajectory of site condition to the 50-year planning timeline. For the purposes of the illustration, all sites are assumed to continue toward the more heavily altered condition, though actual site trajectory can improve, depending on local stressors.

4) confirmation of actual benefits as determined from monitoring and adaptive management (Fischenich et al. 2013). Quantifying future ecological states hinges on selecting appropriate metrics and establishing a correspondence to the specific objectives they measure.

Traditionally, project planners have quantified the future ecological state by comparing the quantity and quality of habitat for the with- and without-project condition over a 50-year planning horizon (Figure 2). Quality is typically ascribed using an index from zero to one with one representing an "ideal" habitat. When the quality index is multiplied by an area, the output is referred to as a "habitat unit." The term "ecological lift" is used to describe the difference between the trajectory lines in Figure 2, and reflects the net benefits of the project over the project planning period (50 years). This net benefit can be divided by the number of years to establish an annualized benefit.

**An alternative reference-based approach.** The traditional approach described above has been criticized for several technical reasons related to the underlying assumptions of the methodology, but also notably because it overlooks benefits not specifically related to habitat. As

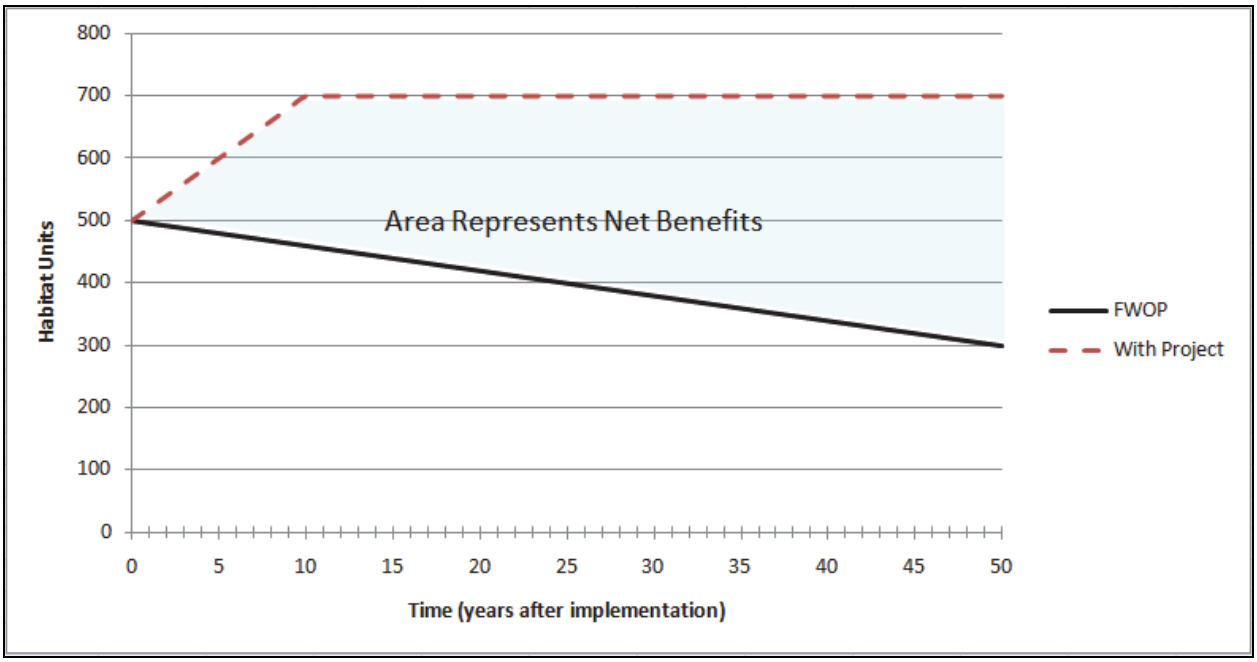


Figure 2. Net benefits in terms of habitat units calculated by the difference in the future with- and future without-project (FWOP) conditions over a 50-year planning horizon.

an alternative, the habitat quality scalar can be replaced by an index reflecting the condition of the system relative to a suitable "reference" based upon a suite of parameters reflecting the ecosystem structure and function (Fischenich et al. 2013). Utilizing reference conditions as a scalar for the "quality " component of the traditional habitat assessment approach has potential to greatly improve the EBA process if the reference conditions:

- Are not limited to habitat but include hydrologic, geomorphic, biogeochemical, and other metrics and associated indices.
- Provide a visualization of targeted conditions with supporting data regarding the achievable level of function.
- Facilitate the process of determining metrics, success criteria, and performance standards based on achievability within the context of the particular ecosystem type and ecoregion for the project.
- Provide a standard for testing and verification of selected metrics, conceptual and assessment models, and means of scaling restoration benefits.
- Establish natural temporal variation in ecosystem processes, benefits, and metrics.
- Provide a rapid means, by comparison, of determining success and adjusting the monitoring and contingency plan (i.e., adaptive management).

**Requirements for applying reference concepts.** The process of establishing reference conditions and concepts can be useful in setting restoration or mitigation targets and priorities;

developing ecosystem restoration designs, monitoring, and sustainability; and identifying and evaluating restoration success criteria (Miller et al. 2012). An appropriate aquatic ecosystem reference condition should possess certain characteristics:

1. An ecosystem type or class representative of the desired restoration action of the restoration project.

2. Qualities similar to the restoration project, including the following considerations/properties:

    a. Landscape and watershed position, orientation, and scale.

    b. Water source(s), geomorphology, and hydrodynamics.

    c. Sediment and coarse woody debris dynamics.

    d. Soil properties such as plasticity, structure, particle size distribution, drainage class, geochemistry, etc.

    e. Ecological structure and habitat.

    f. Same ecoregion context.

    g. Similar elevations.

The reference system criteria listed above include several considerations that might not be applicable to all restoration projects and scenarios.

**REFERENCE SELECTION PROCESS:** Selection of an inappropriate reference condition may compromise the success of an ecosystem restoration project. Development of an ecosystem restoration plan begins with selection of an appropriate reference approach, which starts with classic scientific methodology, including statement of the problem, noting the existing state or condition of the ecosystem, and identifying the preliminary opportunities to restore ecosystem structure, function, and processes, which effectively enhance environmental benefits and services (Figure 3). In order to identify a suitable reference approach and condition, it is paramount that statement of the problem and noting the existing state and function of the restoration project are defined clearly and precisely in the context of the surrounding landscape, including stressors (McKay et al. 2010). This is accomplished by starting with ecosystem classification. The importance of ecosystem classification cannot be over-emphasized (Miller et al. 2012). In the following sections, the importance of ecosystem classification is discussed, a template for selection of a pertinent reference approach is outlined, and the reference condition index concept is presented as a means of ecosystem restoration planning.

**Classification (general).** Selection of an appropriate reference approach necessitates accurate classification of the restoration project in not only its current state but also past and potential conditions, as well (Miller et al. 2012). In ecological terms, classification is the systematic arrangement of plants, animals, and geomorphic characteristics in groups or categories according to established criteria, common properties, intrinsic characteristics, or associations. Gauch (1982)

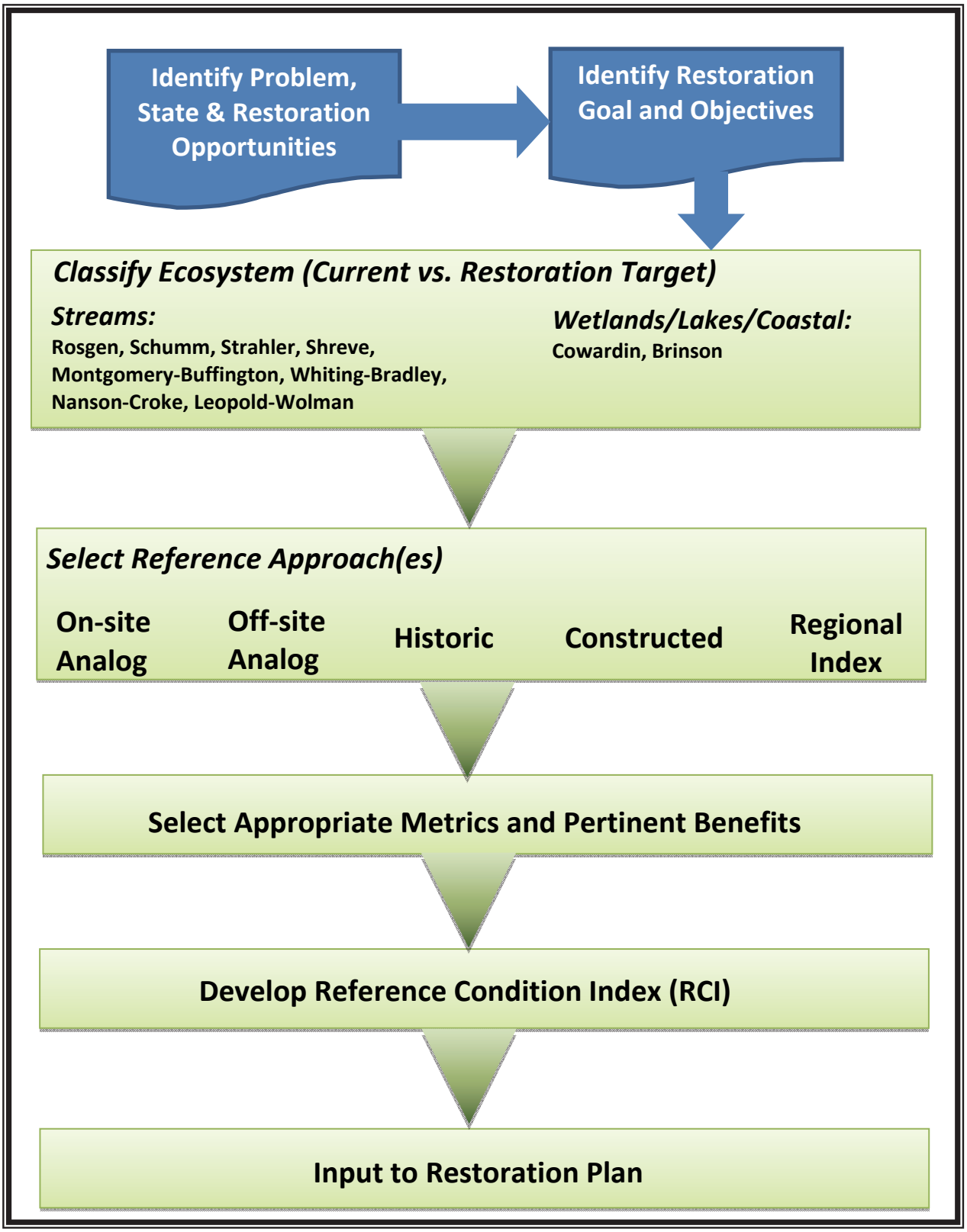


Figure 3. Reference approach selection process.

described classification as a means of "grouping similar entities together." The seasoned scientist is capable of predicting ecosystem behavior (including functions and benefits) by using a classification system that adequately characterizes the ecosystem's geomorphological, physiochemical, and biological attributes. In addition, ecoregion scale factors such as patterns in land use, land surface form, potential natural vegetation, and soils (Omernik 1987) should be considered, as well.

**Classification systems.** Several classification systems have been published predominantly for stream ecosystems (Davis 1899, Melton 1936, Platts 1980, Matthes 1956, Lane 1957, Culbertson et al. 1967, Thornbury 1969, Khan 1971, among others). Single classification systems probably do not adequately address aquatic functions, benefits, and services in most cases. Consequently, the use of classification systems in combination and modifiers (e.g., channel stability rating, bank erosional processes) across ecoregion scales is recommended as described below. This technical note addresses aquatic ecosystem classifications that are appropriate to EBA. The following classification systems were rated low, moderate, or high based on the degree to which the classification provides the foundation to evaluate environmental benefits and services (Table 1).

## WETLANDS:

**Classification of wetlands and deepwater habitat.** In 1979, a comprehensive classification of wetlands and deepwater habitats was developed for the U.S. Fish and Wildlife Service (FWS) (Cowardin et al. 1979). Under this system, wetlands were segregated into two major categories, *coastal* (tidal or estuarine) and *inland* (non-tidal, freshwater or palustrine). Pursuant to the Wetlands Resources Act (1986, with amendments in 1988 and 1992), the FWS uses the Cowardin classification system to map and inventory wetlands throughout the United States, predominantly for analysis of trends in wetland status. The Cowardin system uses a three-leveled hierarchical approach: systems, subsystems, and classes. Because the predominant water source and permanency can be gleaned at the system and subsystem levels (e.g., lunar tidal, overbank), wetland processes and functions that affect benefits and services can be assumed. However, National Wetland Inventory (NWI) maps may not include all wetlands within a given geographic region (Tiner 1997). Consequently, the functions and services of wetlands and deepwater habitats may need to be extrapolated in some instances using other wetland inventories in conjunction with the NWI maps.

**Hydrogeomorphic classification.** The hydrogeomorphic system (HGM) classifies wetlands based on three criteria: geomorphic setting, water source, and hydrodynamics (Brinson 1993). Wetlands are segregated based on features that fundamentally influence how they function (Ainslie et al. 1999). In light of a classification system that constructs the foundation for a functional assessment protocol, ecosystem benefits and services pertinent to wetland ecosystems can be described with a high degree of confidence using HGM.

## STREAMS (GENERAL):

**Floodplain classification.** Based on stream power and sediment properties, Nanson and Croke (1992) recognized three classes of floodplains: high-energy non-cohesive; medium-energy non-cohesive; and low-energy cohesive. Thirteen orders and suborders were defined based on

**Table 1. Selected classification systems with relative application to EBA.**

| Classification | Author(s) | Key Properties | Primary Use | EBA Utility |
|---|---|---|---|---|
| ***Wetlands:*** | | | | |
| Classification of Wetlands and Deepwater Habitat | Cowardin et al. 1979 | System, Class, Subclass | National Wetland Inventory Mapping & Status | Moderate |
| Hydrogeomorphic Classification | Brinson 1993 | Geomorphic Setting, Water Source, Hydrodynamics | Assessment of Wetland Functions | High |
| ***Streams (General):*** | | | | |
| Floodplain Classification | Nanson and Croke 1992 | Stream power & sediment properties | Classification Based on Alluvial Sediment | Low |
| Channel Patterns | Leopold and Wolman 1957 | Braid Formation Stages | Planform | Low |
| Channel Evolution Model | Schumm et al. 1984 | Five Stages of Channel Evolution | Sequential Changes in Channel Geometry | Moderate |
| Channel Evolution Model | Simon 1989 | Similar to Schumm with additional "Constructed" stage | Channel Stages Following Modification | Moderate |
| Natural Rivers Classification | Rosgen 1994 | Planform, cross-sectional geometry, and longitudinal profile | Stream Assessment, Restoration | High |
| ***Streams (High Gradient):*** | | | | |
| Channel-Reach Morphology | Montgomery and Buffington 1997 | Classification based on bedform types | Mountain physiography – in channel | Moderate |
| Channel-Reach Morphology | Whiting and Bradley 1993 | Process-based, dominant physical processes | Mountain physiography – hillslope & in channel | Moderate |
| ***Channel Network Order:*** | | | | |
| Stream Order | Strahler 1952 | Relative position in network | Define stream size & relative watershed position | Low |
| Stream Magnitude | Shreve 1967 | Stream linkage | Define stream size & relative watershed position | Low |
| ***Combined Classifications:*** | | | | |
| Rosgen / Schumm or Simon | Combines planform and instream geometry with channel adjustments | | | Very High |
| Whiting and Bradley / Shreve | Combines hillslope and valley properties with stream magnitude | | | High |

nine floodplain-forming processes. In recognition of dynamic geomorphologic processes common to active floodplains, floodplain transformations were addressed.

**Channel patterns.** Leopold and Wolman (1957) developed a correspondence between planform, cross-sectional geometry, and longitudinal profile, with subsequent bedform

maintenance described in the context of the three planform patterns: straight, meandering, or braided. The authors suggest that along a stream continuum, the different patterns intergrade. In recognition of this observation, assessment of ecosystem benefits and services is likely to be limited if based upon this classification system, with benefits derived predominantly from a very coarse description of habitat diversity.

**Channel evolution models.** Schumm et al. (1984) introduced an assessment method based on five sequential evolutionary channel stages in regards to channel cross-sectional geometry. Later, Simon (1989) proposed an additional channel stage named "constructed" (Stage II of VI). Both authors provided channel evolutionary processes from a stable (Simon, "premodified") form through a series of geomorphologic adjustments back to a stable form (Simon, "restabilization"). In conjunction with modifiers based on stream typology and ecoregion, ecosystem benefits and services can be described with a moderate degree of confidence using this method.

**Natural rivers classification.** Rosgen (1994) presented a stream classification system based on cross-sectional geometry, channel planform, and longitudinal profile (dimension, pattern, and profile, respectively). His classification was successful in combining channel morphological characteristics utilized in the aforementioned stream classification systems into seven major stream classes. In addition, Rosgen's stream typology included associated ranges in entrenchment ratio and channel slope. He also attempted to include evolutionary stages in channel adjustment using stream classification in general (Rosgen and Silvey 1996), and incised streams (Rosgen 1997) in particular. In the Lower Weminuche River, Colorado restoration, for example, an incised channel (F4) resulted in excessive bank erosion, lowering of the water table, loss of meadow productivity, and fish habitat degradation (Rosgen 1997). The stream was restored to a C4 channel by blocking flow to the incised channel and re-introducing flow to the historic channel. Functional restoration and associated benefits included re-coupling the bank-full event to the meadow (food chain support) and improved fish habitat. In conjunction with regional application (e.g., ecoregion) and functional assessment, the utility of assessing ecosystem benefits and services using Rosgen's classification system is high.

## STREAMS (HIGH GRADIENT):

**Channel-reach morphology.** Two separate methods of classification were evaluated for high-gradient streams predominantly located in mountainous physiography. Montgomery and Buffington (1997) developed a stream classification based on sediment source (colluvial versus alluvial) and bedform types (cascade, step pool, plane bed, pool riffle, and dune ripple). Given that aquatic habitat diversity is dependent, in part, on the diversity and type of bedforms, inferences to functions and benefits can be made. However, the stream restoration design may require additional reach-specific data such as planform and cross-sectional geometry.

Similar to the previously described classification, the basis of the headwater classification developed by Whiting and Bradley (1993) was predicated on an understanding of dominant physical processes. However, in contrast to Montgomery and Buffington, the Whiting and Bradley classification included hill slope and valley components in addition to channel and sediment properties: hill slope gradient, valley width, channel width, channel gradient and depth, and sediment size. Consequently, natural conditions and anthropogenic disturbances at the hill

slope and valley scales are elucidated. The utility of assessing ecosystem benefits and services using headwater classification systems is moderate.

## CHANNEL NETWORK ORDER:

**Stream order and magnitude.** Strahler (1952) and Shreve (1967) developed channel order systems relevant to drainage analysis (i.e., relationship between stream length and stream order). In both approaches, stream orders are used to define stream size based on a hierarchy of tributaries. However, the approaches are different in regards to treatment of streams at their confluence or node. The Shreve system assigns a magnitude of one to each exterior link in the drainage network and each subsequent link downstream is the sum of the links that form it. In contrast, the Strahler system requires stream links of the same order to produce a higher order downstream. The utility of assessing ecosystem benefits and services using channel network order is low.

## COMBINED CLASSIFICATIONS:

**Rosgen / Schumm or Simon.** There are direct relationships between selecting an appropriate classification system,identifying a suitable reference approach, and assessing functions and benefits. However, because single ecosystem classification systems were designed, in general, for a specific application, treatment of important ecosystem characteristics may be limited in any single system. In light of that fact, use of multiple classification systems, in certain cases, broadens the application and improves the confidence in selecting a robust reference approach. For example, Rosgen (unpublished course training materials) combined natural channel classification (Rosgen 1994), channel reach morphology (Montgomery and Buffington (1997), Wolman pebble count (Wolman 1954), and channel stability rating (Pfankuch 1975). In a different study conducted on the Big Creek watershed located in the Piedmont of Georgia, Fischenich (1999) combined Rosgen's classification, Schumm's channel evolution model, channel protection properties, and bank erosional processes.

**Reference condition index.** Developing a reference condition index (RCI) offers a means of normalizing the restoration site against the characteristics and properties (metrics) of a reference condition. RCI is similar to the functional capacity index (FCI) used in the hydrogeomorphic approach to wetland functional assessment (Smith et al. 1995). However, this technical note presents the use of RCI in other aquatic ecosystems, as well.

Conceptually, an RCI is a metric that defines the relationship between the value of an ecosystem attribute or suite of attributes at a restoration site and their corresponding values in a reference ecosystem. By convention, when the value of an ecosystem attribute is within the range of values exhibited in a reference ecosystem, an RCI value of 1 is assigned. As the value of the ecosystem attribute increasingly departs from this range of values, a lower RCI value is assigned. For example, consider the ecosystem attribute tree basal area. Using the minimally disturbed condition (MDC) reference, mature, bottomland hardwood (BLH) forests typically have tree basal areas that range from 25-30 $m^2$/ha (Smith et al. 1992, Messina and Conner 1984). As illustrated in Figure 4, a BLH ecosystem with tree basal area within this range is assigned an RCI of 1.0. Now consider a restoration project with the objective to restore agricultural lands to a BLH ecosystem. Prior to restoration, an RCI of 0 is assigned to the tree basal area attribute

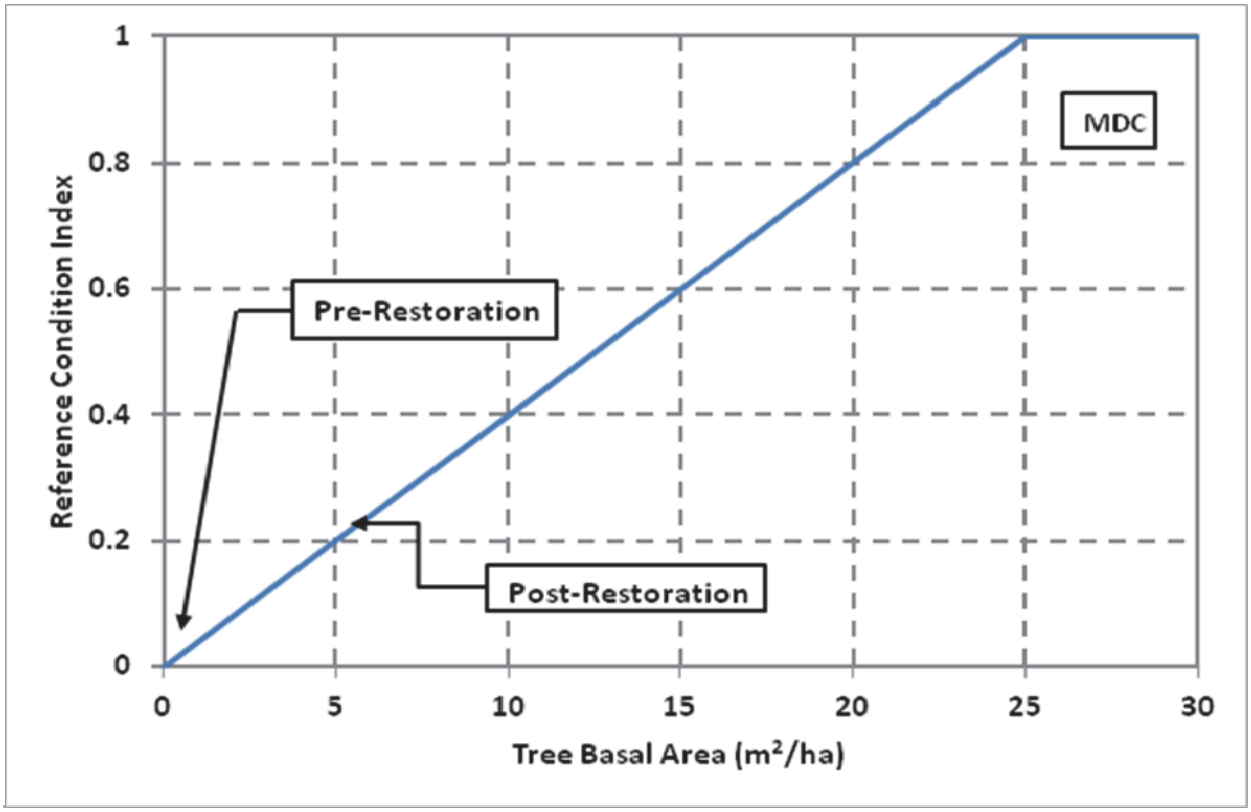


Figure 4. Relationship between tree basal area and reference condition index for the minimum disturbed condition (MDC) reference approach.

because no trees are present (i.e., tree basal area is 0.0 $m^2$/ha). During the restoration of the site, trees are planted, and tree basal area increases to 5 $m^2$/ha, and consequently, the RCI increases to 0.2 (note that in this example a linear relationship between tree basal area and value is assumed). The increase in RCI between pre- and post-restoration can be interpreted as a relative measure of environmental benefits resulting from the restoration project. Any simple ecosystem or landscape attribute can be evaluated in the same manner, provided that a relationship between the ecosystem attribute value and the reference condition can be established.

A similar process can be applied to synthetic metrics. For example, the RCI for a synthetic metric representing the vegetation condition could be based on combining the RCI values of multiple ecosystem attributes related to the vegetation condition (e.g., basal area, stem density, cover, and number of vegetation strata, species composition, and species richness). Further, the RCI values of multiple synthetic metrics, representing various aspects of the ecosystem such as vegetation condition, hydrologic condition, fauna condition, biodiversity condition, or landscape condition, could be combined into an RCI value for a synthetic metric representing the overall ecosystem condition. The RCI provides a standardized metric for the relationship between the value of ecosystem attributes and the reference condition. Environmental benefits can be measured based on the change that occurs in the RCI between the pre-restoration state and post-restoration.

An important characteristic of an RCI is that it allows for the comparison of environmental benefits between the same types of ecosystems as well as between different types of ecosystems.

For example, consider that two projects, restoring different types of ecosystems, develop a synthetic "vegetation condition" metric based on combining the RCI values of several simple vegetation metrics that appropriately characterize vegetation in the ecosystem type. Assuming that the synthetic vegetation condition metrics for both ecosystems accurately reflect the range of the vegetation condition, the environmental benefits of the two projects could be contrasted, in the context of the vegetation condition, by comparing the change in the vegetation condition RCI from the pre-restoration to the post-restoration condition. It does not matter that different simple vegetation metrics are used in the two cases, because the value of an ecosystem attribute always relates to the RCI in the same manner.

**Comparability of RCI for different reference conditions.** The RCI is conceptually simple, but there are a number of challenges to its development. One of these is that when restoration projects use a different reference condition (e.g., historic condition pre-disturbance (HCPD) or least disturbed condition (LDC)), the resulting RCI may not be comparable. This is because the potential range of values exhibited by an attribute in all ecosystems in the reference domain (i.e., undisturbed to extremely disturbed) will differ depending on the reference condition selected to represent it. This is illustrated in Figure 5 for the tree basal area attribute. Under the MDC reference, the potential range of values is 0-15 $m^2$/ha, but under various LDC references, the potential range of attribute values varies from 0-10 $m^2$/ha. RCI values that are based on two different potential ranges of values are not comparable, except as described in the example above where the MCD is used for two different systems. Consider the situation where one restoration project uses reference ecosystems that exhibit the MDC reference, and a second restoration project uses ecosystems that exhibit an LDC reference. As shown in Figure 4, under the MDC reference, the range of values for the tree basal area attribute is 25-30 $m^2$/ha in reference ecosystems, while the potential range of values for the tree basal area in all ecosystems in the reference domain is 0-30 $m^2$/ha. In the second restoration project, under the LDC reference category, the range of values for the tree basal area in reference ecosystems is 9-10 $m^2$/ha, while the range of values for the tree basal area in all ecosystems in the reference domain is 0-10 $m^2$/ha (Figure 6). In both restoration projects, the RCI under the pre-restoration condition is 0 (i.e., no trees present). After tree planting, the RCI for the first restoration project increases to 0.2 (Figure 4), while the RCI for the second restoration project increases to 0.5 (Figure 6). At both restoration projects, the increase in RCI is a potential measure of environmental benefits. However, because the range of tree basal area in all ecosystems is greater under the MDC scenario than the LDC scenario, the relationship between an ecosystem attribute and the selected reference condition (i.e., RCI) is different. The change in RCI (i.e., environmental benefits) for the project using LDC (0 to 5) is overestimated in comparison to RCI using the MDC (0 to 0.2). Although the two projects achieved the same actual lift, the two restoration projects are not comparable using RCI in this manner.

One solution to this challenge is for all restoration projects to use the same reference condition. However, not all reference condition categories are suitable. The LDC reference is problematic because the potential range of attribute values can differ depending on the degree of system-wide disturbance and the numeric difference between MDC and LDC. While the MDC reference condition should be suitable because the range of attribute values is typically the same within ecosystem types, there are other problems with the MDC reference. The first is that if no existing ecosystems exhibit the MDC reference, a hypothetical ecosystem must be constructed to represent the MDC reference condition. The second problem relates to whether or not it is

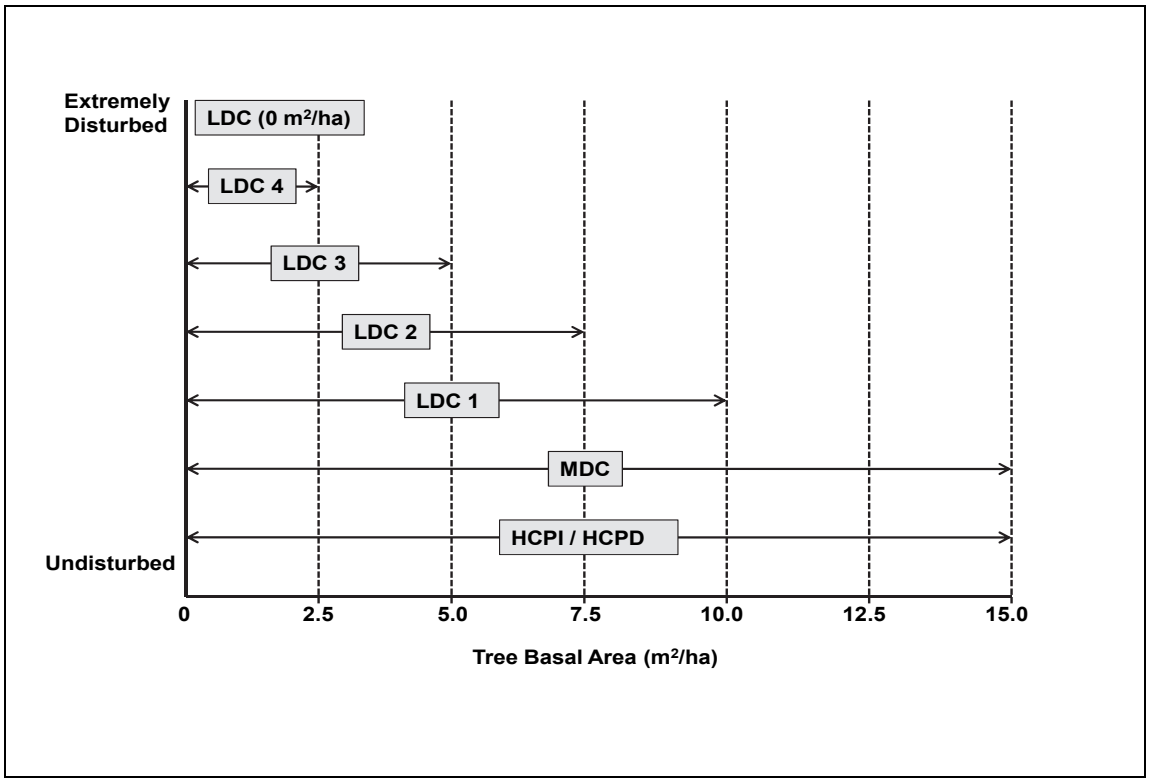


Figure 5. Range of potential values for the tree basal area attribute under various reference conditions. LDC = least disturbed condition, MDC = minimally disturbed condition, HCPI = historic condition: pre-industrial, and HCPD = historic condition: pre-disturbance.

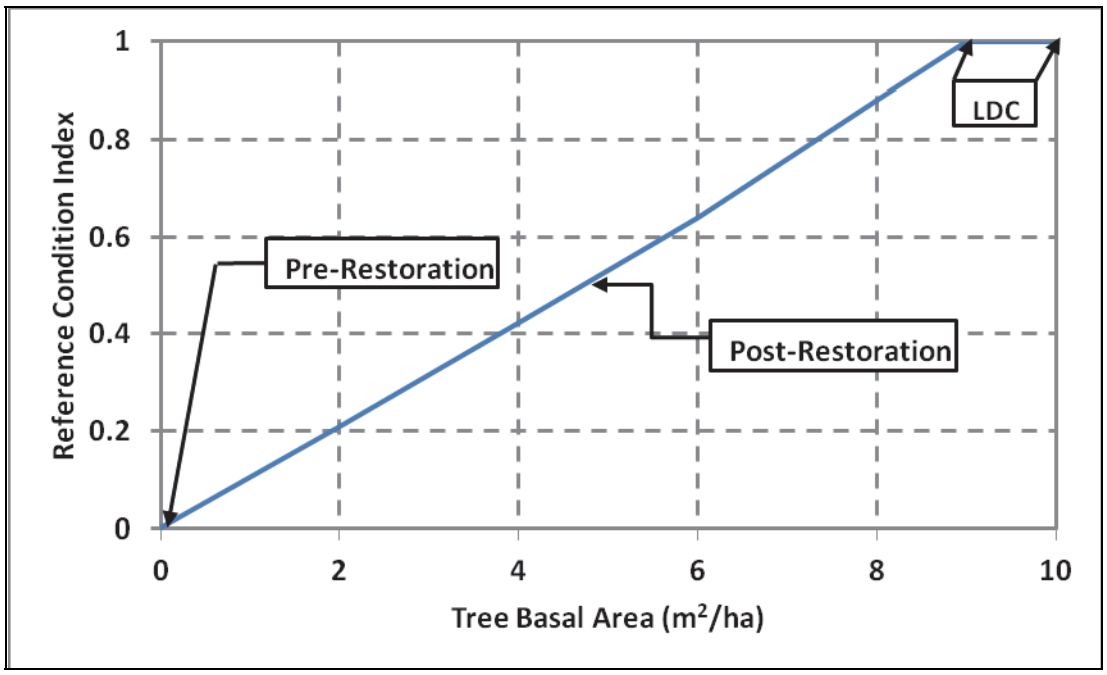


Figure 6. Relationship between tree basal area and reference condition index for the least disturbed condition (LDC) reference approach.

appropriate to use the MDC reference condition under certain conditions. For instance, when an ecosystem or landscape has passed a threshold of irreversibility or has an irreversible constraint, it may represent an ecosystem type that is different from the original or different from the ecosystem that should be there under ideal conditions. Identifying ecosystem thresholds, as illustrated in Figure 7, is becoming increasingly significant in ecosystem assessment. However, determination, forecasting, and detection of this threshold are difficult (Scheffer 2009).

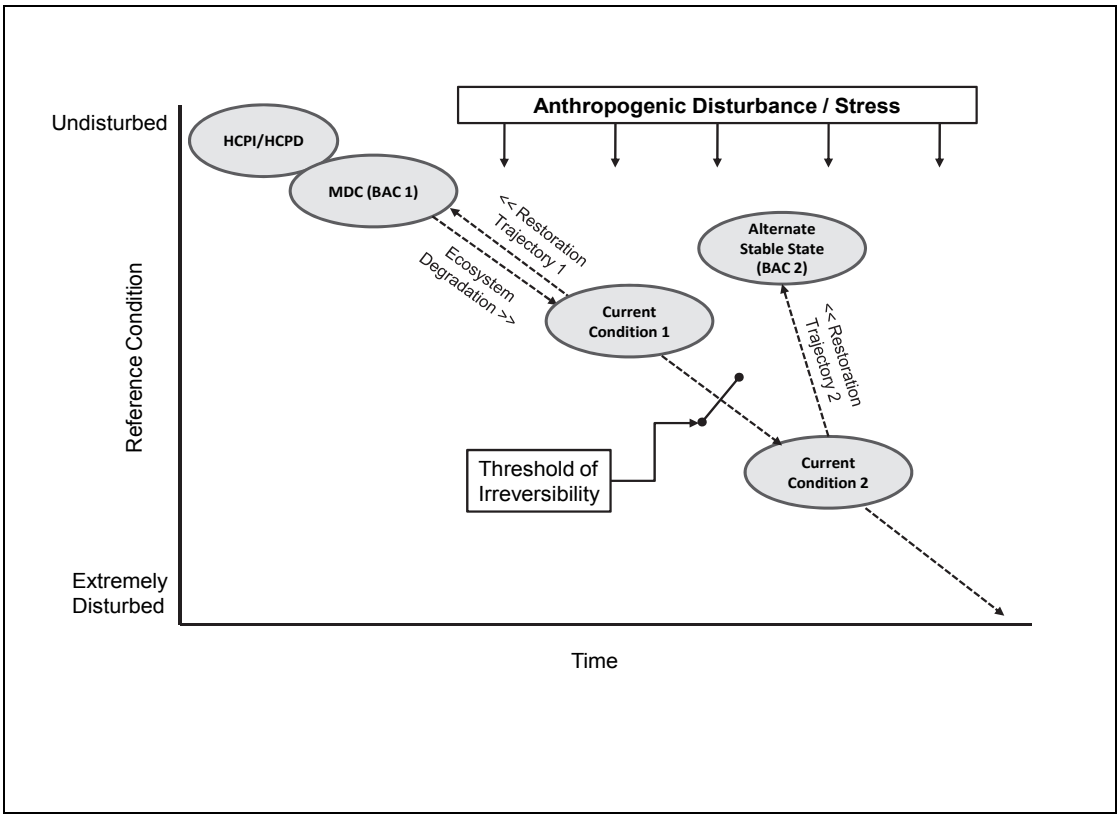


Figure 7. Alternative restoration trajectories for different restoration projects on opposite sides of the threshold of irreversibility. HCPI = historic condition: pre-industrial, HDPD = historic condition: pre-disturbance, MDC = minimally disturbed condition, BAC = best attainable condition.

In general, the ecosystem threshold of irreversibility can be defined, in this context, as the point where the critical threshold of degradation has been reached such that return to previous conditions is unlikely. For example, if the hydrologic regime of a stream system has been irreversibly altered by dams, interbasin transfer, or diversion, the pre-disturbance or MDC reference is not achievable through restoration. This raises the question "should the MDC be replaced with a best attainable condition (BAC) reference to reflect the current constraints?" If the answer is yes, then the BAC reference is suitable for evaluating environmental benefits. This is illustrated in Figure 7 for two restoration projects. Under current conditions, the first restoration project has not passed the threshold of irreversibility and can be restored along Restoration Trajectory 1 toward the MDC (i.e., BAC 1) reference. The second restoration project has passed the threshold of irreversibility and cannot be restored to the MDC reference. It can, however, be restored toward an alternate stable state, or the BAC 2 reference. The important

question is which option is more appropriate when comparing RCI values from a restoration project: using an RCI value of 1 that is tied to the BAC reference representing the original MDC reference, or using an RCI value of 1 that is tied to the BAC reference representing an alternate stable state.

Another means of dealing with the lack of comparability is to truncate the RCI axis to reflect the position of the LDC reference relative to the MDC reference. As shown previously, when the MDC reference in the first restoration project (Figure 4) and LDC reference conditions in the second restoration project (Figure 6) were compared using an RCI axis scaled from 0-1, a change in the tree basal area attribute results in a change in RCI that is not comparable.

In Figure 8 the RCI axis for the LDC reference has been truncated and is limited to a value of 0 to 0.5. Truncating the RCI axis to 0.5 in this case is based on an estimate of the position of the LDC reference condition on the RCI axis relative to the MDC reference if the MDC is known. By again applying the tree basal area ecosystem attribute from above, the tree basal area attribute in the first restoration project ranges from 0-30 $m^2$/ha to match the tree basal area in the second restoration project from 0-10 $m^2$/ha . Post-restoration RCI values for both projects now reflect the same amount of change: 0 to 0.2. The relationship between the ecosystem attribute and the RCI is similar, and the change in the RCI (i.e., environmental benefits) for the two restoration projects is comparable.

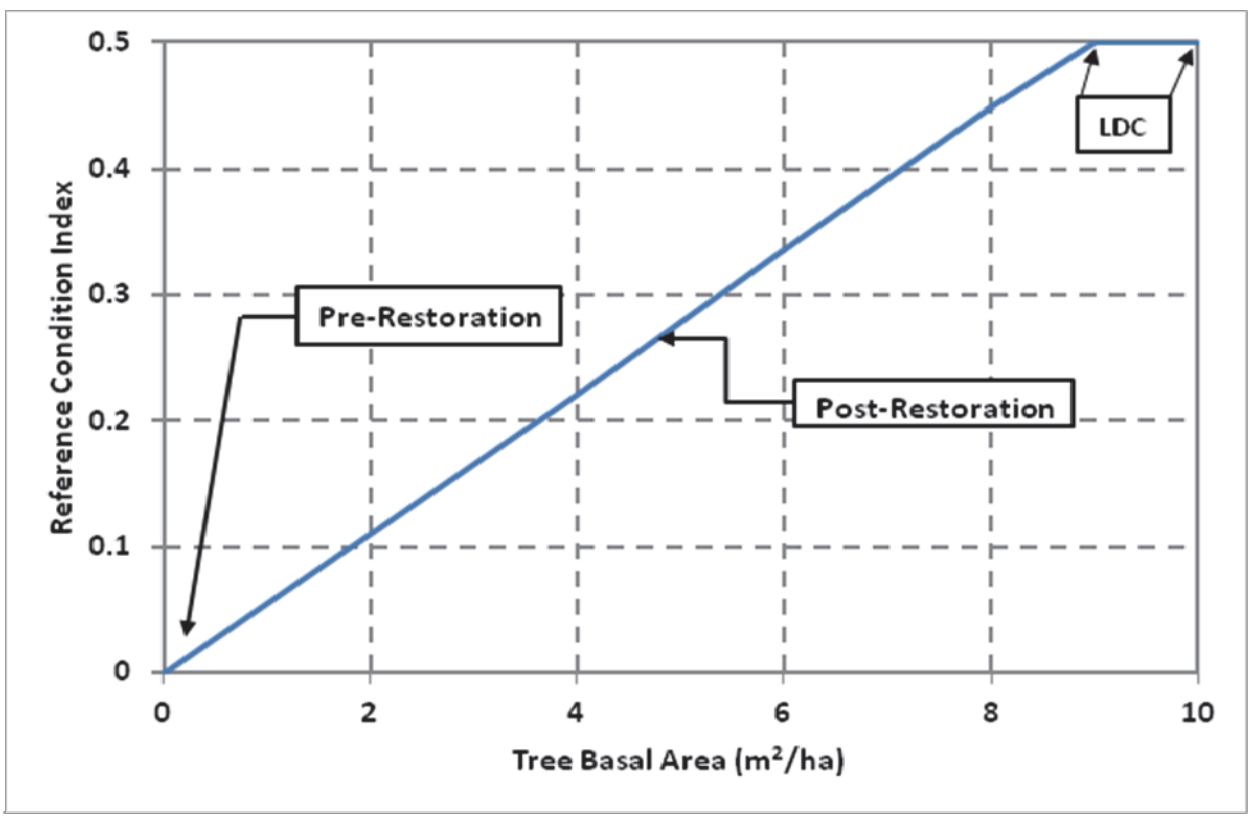


Figure 8. Relationship between tree basal area and RCI for the LDC reference approach with the truncated reference condition axis.

A variation on this solution would be to define categories of RCI a priori based on the type and degree of disturbance (Figure 9). Restoration projects using the LDC or BAC reference would simply truncate the RCI axis at the level that corresponds to the type and degree of disturbance observed at a specific restoration project. This is similar to the approach proposed by Davies and Jackson (2006) for defining disturbance "tiers" along a biological condition gradient. The challenge in using this approach is to reduce a potentially large number of least-disturbed condition scenarios into a reasonable number of categories.

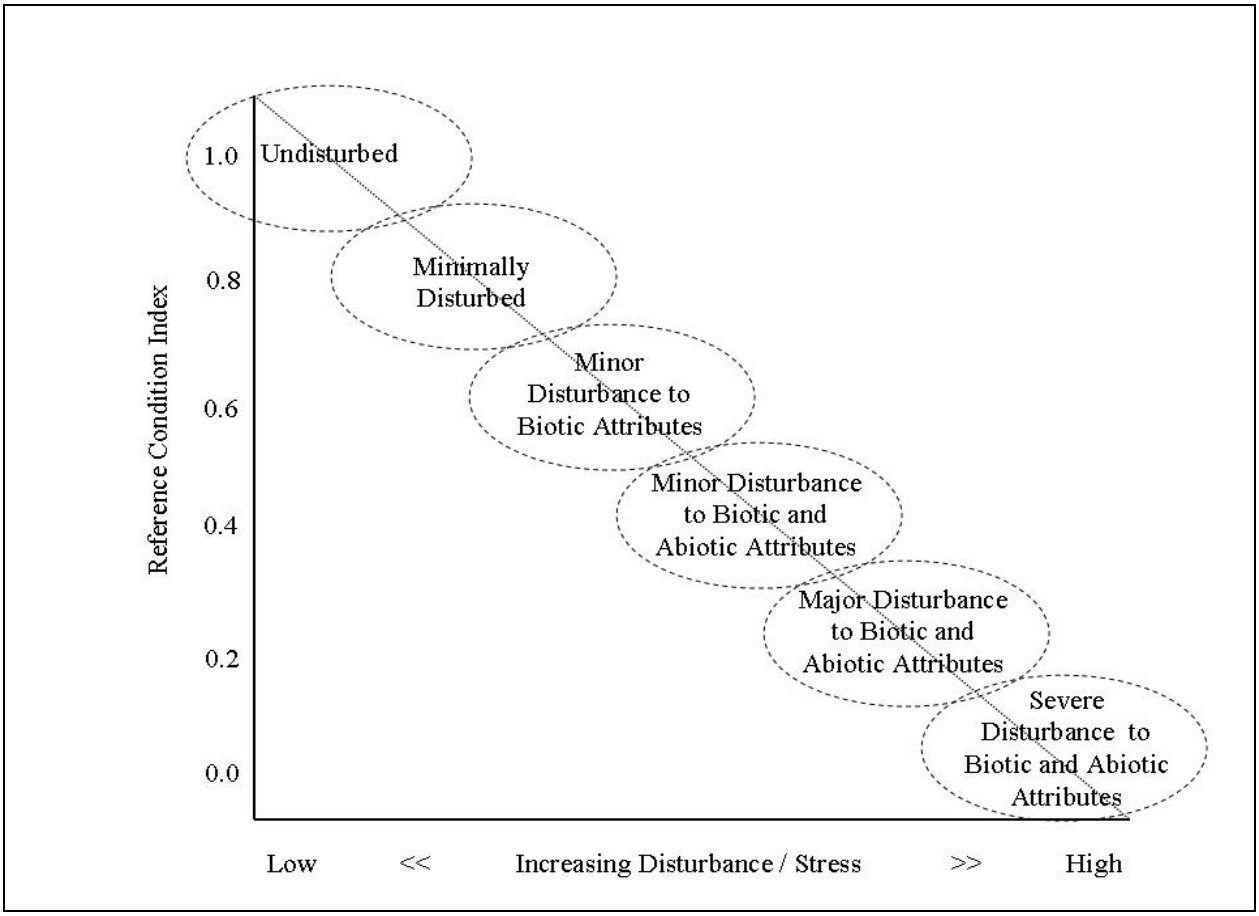


Figure 9. Potential reference condition tiers for defining the relationship between the level of ecosystem degradation and the reference condition index.

**Evaluating environmental benefits challenges.** There are several generic challenges related to the development of a metric such as RCI to evaluate and compare environmental benefits within and across restoration projects. First, restoration projects with differing objectives will have different ecosystem attributes that serve as performance criteria. Consequently, one restoration project may result in environmental benefits related to hydrology, another may result in environmental benefits related to vegetation, and another may result in environmental benefits related to animal species. For example, consider two completed restoration projects; the first restoring the hydrologic regime of a stream channel by altering the release schedules from an upstream dam and the second restoring the hydrologic regime by replacing invasive vegetation with native vegetation. Under the first scenario (release schedules), one of the ecosystem

attributes used for design and success criteria was daily discharge at the restoration site. The RCI value of daily discharge pre-restoration was 0.5 and after restoration was 1.0 (i.e., return to the MDC reference), resulting in a change in RCI value of +0.5 (i.e., the environmental benefit). Under the second scenario (vegetation), one of the ecosystem attributes used for design and success criteria was species composition. The RCI value of species composition was also 0.5 and after restoration was 1.0, resulting in a change in RCI value of +0.5. Based on the change in RCI, the environmental benefit from the first scenario is the same as the second scenario, both proportionally compared to the total range and as an absolute unit RCI increase. The question that is difficult to answer is whether it is acceptable to compare an environmental benefit related to hydrology to one related to vegetation.

One possible solution to this challenge would be to evaluate all restoration projects using a standardized suite of ecosystem and landscape attributes (Kelly and Harwell 1990). For example, the standardized suite could include synthetic metrics that consider a range of ecosystem and landscape attributes such as hydrologic condition, vegetation condition, fauna condition, and landscape condition. The overall environmental benefits for the restoration would be a synthetic metric (i.e., ecosystem condition) based on combining the RCI values of the standardized suite of synthetic metrics. The ecosystem condition metric could be normalized so if one or more of the standardized metrics was not relevant at a restoration project (i.e., hydrologic condition in a terrestrial restoration project), the ecosystem condition metric would still be comparable across restoration projects.

Various standardized criteria for evaluating ecosystem and landscape restoration have been proposed and may be useful in creating a suite of standard ecosystem condition categories that can be applied to many restoration projects to enable more generalized benefits comparison. Palmer et al. (2005) proposed “standards for ecologically successful river restorations” that included: 1) creation of an accompanying image of dynamic state, 2) ecosystem improvement, 3) increase in resilience, 4) no lasting harm to ecosystem, and 5) complete ecological assessment. They also identified guidelines and potential indicators for evaluating the criteria, and encouraged further work to determine the feasibility of implementation. Similarly, Lubinski and Thieling (1999) and Lubinski (1999) proposed six criteria for assessing the “ecological health” of floodplain reaches on the Upper Mississippi River. The criteria included: 1) viable native populations and supporting habitats, 2) ability to recover from disturbances, 3) ecosystem sustainability, 4) capacity to function as part of a healthy river basin, 5) annual floodplain connectivity, and 6) ecological value of natural disturbances. The criteria were evaluated based on various factors, and assigned one of four “grades” including: 1) unchanged/recovered, 2) moderately impacted, 3) heavily impacted, and 4) degraded. The above criteria are similar to the approach proposed by Davies and Jackson (2006) in which disturbance “tiers” were defined along a biological conditions gradient. Eighteen “vital ecosystem attributes” (Aronson et al. 1993) and sixteen “vital landscape attributes” (Aronson and Le Floc’h 1996) have been proposed to serve as quantitative indicators of ecosystem and landscape degradation. Fischenich (2006) proposed a suite of 15 functions that should guide stream restoration, and these functions have subsequently been used as a basis for a mitigation framework proposed by USFWS and EPA (Harman et al. 2011). The above examples provide evidence that the use of standardized criteria has potential and deserves further exploration for application to an ecosystem condition index in a restoration context.

Another generic challenge that must be addressed in developing a metric to evaluate environmental benefits relates to how the geographic size of a restoration area is incorporated into the evaluation of environmental benefits. For example, consider two restoration projects where the reference ecosystems, reference approach, restoration goals and objectives, and design and success criteria are the same. Both restoration projects are complete, and the environmental benefits are evaluated based on the synthetic ecosystem condition RCI proposed above. The difference between the pre- and post-restoration RCI values for both restoration projects equals +0.4. The only difference is that the first restoration project restored 100 acres and the second restored 10 acres. Clearly, the environmental benefits at the larger restoration site are greater assuming the cost-effectiveness and incremental cost on a per acre basis are equal (Fischenich et al. 2013). Traditionally, index-based habitat evaluations (i.e., Habitat Evaluation Procedure) and other assessment procedures multiply the habitat suitability index-HSI (i.e., change in RCI value) by the size of the assessment area that is generating the habitat units (HU). The potential of generating reference capacity units from the product of the RCI and the restoration area (acres) needs further exploration.

A final generic challenge that must be considered when developing a metric to evaluate environmental benefits across restoration projects is how should restoration priorities be established? For example, consider two proposed restoration projects. The first proposes to restore 100 acres of endangered species habitat, is expected to cost $100,000, and, based on estimates, predicts a synthetic ecosystem restoration RCI value of 0.5. A second restoration project proposes to restore 100 acres of riparian vegetation, is also predicted to cost $100,000, and, based on estimates, predicts a synthetic ecosystem restoration RCI value of 0.5. Both projects are presented to a potential funding agency with a restoration budget of $100,000 for the year. The question is, on what basis does the agency choose to fund one restoration project over the other? “Since aquatic ecosystem restoration plans generally do not have a monetary benefit-cost-ratio, a cogent benefit justification statement must be included in the recommendations section of the decision document” (Corps of Engineers Civil Works Planning and Policy Division (CECW-PB) 2007). As an integral part of the alternative analysis, relative weights could be assigned to endangered species habitat and riparian vegetation habitat in the context of the ecoregion and watershed associated with each. Restoration priorities could be established based on the relative restoration needs at the watershed scale with consideration for trade-offs.

## APPLICATION TO ENVIRONMENTAL BENEFITS ASSESSMENT:

Reference conditions and concepts are important in nearly all capabilities identified in the Environmental Benefits Analysis Research Program, including construction of conceptual models and selection and testing of appropriate metrics. For a detailed treatise on each of the capabilities discussed below, the reader is directed to the “Framework for Science-Based Environmental Benefits Assessment,” Section 3.0, Overarching Technical Issues (Fischenich et al. 2013). Technical notes specific to each EBA capability are referenced below, as well.

**Conceptual models.** Conceptual models describe or illustrate the functional relationships and energy pathways of an ecosystem. They provide the Ecosystem Restoration Team with several tools necessary to plan and implement successful ecosystem restoration, including, in part:1) an understanding of the problem or cause of functional impairment, 2) a basis for identifying the

cause-and-effect relationship, and 3) a means of identifying appropriate and relevant metrics for monitoring, including performance standards and success criteria (Fischenich 2008). Given the diversity of aquatic ecosystems, an accurate depiction of reference conditions is critical in determining natural background conditions including the normal disturbance regime, response to seasonal and long-term climatic changes, and effects of catastrophic events. By establishing reference conditions, the conceptual model (including benefits and services) can be visualized and communicated more effectively between professionals and stakeholders. In addition, conceptual models that are created and visualized through available analog reference sites can function as effective hands-on teaching and demonstration sites.

**Metric selection and testing.** Establishing reference conditions provides an opportunity to describe both qualitatively and quantitatively desirable system properties including the natural range of variability and temporal behavior of the ecosystem class (McKay et al. 2012). By definition, a metric is a measurable system property or properties that quantify the degree of objective achievement (Reichert et al. 2007). Identifying reference conditions or a suite of reference sites (e.g., HGM, reference domain) provides an opportunity to test metrics along a sliding scale that represents the natural spatial and temporal variability inherent to aquatic ecosystems. The level of confidence in metric suitability when constructing project performance standards and formulating success criteria is greatly improved by metric testing, verification, and refinement based on reference conditions. In addition, the correspondence and rationale between natural and constructed metrics (direct measures) versus proxy metrics (surrogates,McKay et al. (2010)) can be developed more effectively based on reference conditions. Once the relationships between natural and constructed metrics and their surrogates are adequately described, surrogates can be used in conjunction with direct measures to monitor changes in the restoration project and reference conditions. Also, the associated cost and resources required to collect baseline and long-term monitoring data using test metrics can be evaluated and prioritized. For example, metrics that measure multiple functions or benefits from reference conditions can be preferentially selected over a single metric that only measures or represents one function or benefit.

**DISCUSSION AND CONCLUSIONS:** Reference conditions establish a basis for quantifying the range of conditions associated with changing ecosystem states that could be critical to effectively plan, implement, and track successful aquatic ecosystem restoration projects. The application of reference concepts to this need would be a departure from current practice and would require the establishment of appropriate guidelines and tools. The application of one or more classification systems would be required, and consideration for a suite of standard ecosystem attributes may be necessary. Reference conditions also provide a contextual background against which the degree of degradation, range of condition, and benefits of restoration can be measured. Though aquatic ecosystems are diverse and complex, this technical note and its companion technical note (Miller et al. 2012) provide the foundation to establish reference conditions by applying germane reference approaches.

Based on the current state of the science and practice, ecosystem restoration is inherently experimental, for the most part. However, reference ecosystems provide a template and benchmark that can be used in designing and/or comparing enhanced, restored, or created ecosystems. By establishing reference conditions including identification, testing, and verification of appropriate metrics and baseline conditions, a better understanding of specific

ecosystem functions and benefits is achievable. In addition, reference conditions can be utilized to define restoration goals, assess restoration potential, and evaluate restoration success, including forecasting restoration actions. Moreover, formulating reference conditions provides a means to identify ecosystem drivers, changes, and restoration targets applicable to conceptual model construction and monitoring. Thus, the confidence in designing a successful restoration project is ameliorated.

A reference approach suitable for use in ecosystem restoration project planning can be selected based on site-specific historical and/or contemporary conditions as a means of meeting programmatic restoration objectives. Once an appropriate reference approach is selected, a reference condition index (RCI) can be developed that normalizes the restoration site against the properties of the reference condition. Future research and development should focus on the following needs: 1) establishing an appropriate classification system or set of systems to support reference-based restoration and benefits assessment while contributing to other parallel interests such as establishing significance, 2) determining which attributes are appropriate for each ecosystem class so that assessments can be reasonably comparable, 3) providing guidance for selecting reference conditions, and 4) developing regional reference indexes that capture the natural range of ecosystem-specific variability within a given ecoregion or hydro-physiography. The resulting approach should emphasize ecosystem typology and physiochemical and biological processes and functions with application to evaluation of environmental benefits and ecosystem restoration.

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