OVERVIEW: Urbanization presents a significant threat to the physical, chemical, and biological condition of stream ecosystems as well as associated wetlands and riparian zones. Constraints of developed areas (e.g., unmovable infrastructure) often limit options for urban stream restoration as well as the potential for ecological improvement. Reference conditions are often used in ecosystem restoration as benchmarks against which success (or failure) may be measured, and their use can be particularly valuable in highly altered areas. This technical note presents a generic approach to development and application of a “reference condition index” (RCI) for evaluating the relative success of restoration actions in altered urban environments. Key considerations in development of the RCI are presented through three brief case studies related to the ecological impacts of impervious surfaces, water quality benefits of forest cover, and chemical impairment from industrial effluent. The RCI provides a straightforward set of methods for meaningfully rescaling ecological metrics, quantitatively incorporating reference conditions into environmental benefits analyses, and increasing understanding through clear communication of project outcomes.

INTRODUCTION: In 1972, the Water Pollution Control Act of 1948 was amended to the Clean Water Act, which added, in part, the mandate to restore and maintain the “physical, chemical and biological integrity” of the Nation’s waters. Interpreting this directive, the 2008 Mitigation Rule (U.S. Army Corps of Engineers and U.S. Environmental Protection Agency 2008) defined aquatic ecosystem “condition” as follows:

Condition means the relative ability of an aquatic resource to support and maintain a community of organisms having a species composition, diversity, and functional organization comparable to reference aquatic resources in the region.

Without reference aquatic ecosystems, there is no consistent or recognizable benchmark from which departure from standards could be assessed or measured (Brinson et al. 2006). Establishment of reference condition is, thus, paramount in the assessment of ecological impacts as well as the identification of achievable restoration targets, and application of reference conditions extends throughout the restoration planning and implementation process (Miller et al. 2012, Pruitt et al. 2012). Several methods for the identification of reference conditions are well vetted in the scientific literature addressing targets that range from historically based conditions to best attainable conditions (BAC) (Smith et al. 1995, Stoddard et al. 2006, Fischenich et al. 2013, Miller et al. 2012, and Pruitt et al. 2012). Reference conditions can be derived from a variety of approaches such as on- and off-site analogs, historical conditions, virtual or constructed conditions,
or regional values (Miller et al. 2012). Importantly, significant improvement can be made in setting reference conditions by stratifying regionally (e.g., piedmont v. coastal plain) as well as by ecosystem type (e.g., stream type or size) (Pruitt et al. 2012). Definition of a reference condition can be a crucial guide to many aspects of stream restoration, and readers are encouraged to consult reviews by Miller et al. (2012) and Pruitt et al. (2012) for further information.

Urbanization represents a significant threat to the physiochemical and biological condition of stream ecosystems and associated wetlands and riparian zones. The U.S. Environmental Protection Agency (USEPA) (2000) reported that over 130,000 km of streams and rivers in the United States are impaired by urbanization. These systems often undergo significant change in ecological condition due to hydrologic and geomorphic alterations caused by impervious surfaces (Booth 1991, Paul and Meyer 2001), effects of non-point source pollution from urban runoff on water quality (Klein 1979, Sloane-Richey et al. 1981, Whiting and Clifford 1983, Garie and McIntosh 1986, Winter and Duthie 1998, Paul and Meyer 2001, Wenger et al. 2009), and resulting large-scale cumulative effects on aquatic habitat extent and diversity (Bernaldez et al. 1993, Power et al. 1999, Strange et al. 1999, Wood et al. 1999), as well as a myriad of other changes. Accordingly, urban streams often differ significantly from unmodified, forested streams, and selection of a reference condition for these highly modified systems can be challenging. Although difficult to identify, a reference condition provides a crucial basis for meaningfully rescaling ecological metrics, quantitatively incorporating reference conditions into environmental benefits analyses, and increasing understanding through clear communication of project outcomes.

The objectives of this technical note are three-fold: (1) Identify key issues for establishing reference conditions in urban environments; (2) Propose an RCI for quantitatively assessing urban streams; and (3) Demonstrate the utility and complexity of applying such an index given the constraints normally associated with urban settings.

SETTING REFERENCE CONDITIONS IN URBAN ENVIRONMENTS: Reference standards are established from the aquatic ecosystem(s) that support a suite of processes and functions. A reference condition is the set of attribute values or quantifiable characteristics of the reference ecosystem (Miller et al. 2012). Reference conditions provide a contextual background against which the degree of degradation, range of condition (i.e., reference domain), and benefits of restoration can be measured. Reference condition for restoration design has traditionally been associated with ecosystems that are undisturbed by humans (Hughes et al. 1986, Bailey et al. 2004, Clewell et al. 2004). However, the term has evolved to include a variety of different meanings (See Table 1 in Miller et al. 2012). 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, 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 urban settings, fully functional aquatic ecosystems may not be present or achievable. Without major changes in city planning and management, streams, wetlands, and riparian zones in urban settings may not be restorable to minimally disturbed conditions (MDC) due to constraints that are deemed irreversible, such as:
1. Impervious surfaces and subsequent storm water runoff.
2. Construction of infrastructure such as reservoirs, sediment detention ponds, roads, industries, and homes.
3. Land use intensity such as dense residential or commercial development.
4. Discharge from industry, treated wastewater inputs, and untreated (often inadvertent) wastewater inputs, such as sewer overflows.
5. Chlorine toxicity due to requirements for fecal coliform reduction, water quality standards and/or odor control.
6. Flow reduction due to consumptive uses (water intakes) and basin transfers.

The above constraints and environmental stressors can result in large-scale changes to the hydrologic, geomorphic, and biological structure and function of urban streams. These impacted aquatic ecosystems often do not meet reference standards with regard to their level of functionality. Consequently, the functionality of reference urban streams is established from a subset of urban streams that are considered to have the highest achievable level of functionality, the “best attainable condition” (Stoddard et al. 2006) for a specific type or class of stream. A regional set of reference urban streams could be utilized to develop this template or target toward which degraded systems are then restored.

An appropriate urban aquatic ecosystem reference condition should possess certain characteristics, each of which may not apply to all restoration projects and scenarios (modified from Pruitt et al. 2012):

1. Ecosystem type or class is representative of the system being restored.
2. The reference condition is regionally appropriate (e.g., ecoregion).
3. The reference is similar to the restoration project with respect to landscape position, physical structure and process (e.g., hydrology, geology), and biological structure and process (e.g., species assemblage, habitat types).
4. The reference condition incorporates major underlying constraints on restoration success (e.g., a target for a given level of impervious area).
5. The reference condition is clearly communicated to decision-makers to provide a basis for judgment on the relative standards for success.

Establishing reference conditions and defining restoration targets in urban settings requires: (1) a consideration of the problem in regards to anthropogenic impacts rather than natural causes or random variability, (2) the need to define whether reference conditions refer to pristine conditions, or the range of contemporary conditions based on a suite of reference conditions (reference domain), (3) an expression in quantitative terms of the degree of historic change over time, (4) an account of whether the restoration action is achievable in the current land use setting at both watershed and stream segment scales, and (5) the potential for using past habitat structure and inferred ecological functioning as targets for restoration. It is not only important to reduce contributing sources of impacts, but to be able to redefine reference conditions as boundary conditions change (e.g., under climate change). In urban settings, it is difficult to achieve pristine state; however, a more achievable reference state may be possible (e.g., BAC). Achievability in this context is not only related to economic cost of restoration, but also to the ecological reversibility of the system (Bennion et al. 2011).
A REFERENCE CONDITION INDEX (RCI) FOR URBAN STREAMS: Development of an RCI offers a means of normalizing the restoration site against the characteristics and properties of a reference condition. Conceptually, the 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. The RCI rescales these attributes from 0 to 1 with the convention that 0 and 1 represent the worst and best possible ecosystem conditions, respectively. Thus, any ecosystem attribute can be rescaled by specifying a lower boundary condition (What x-value is associated with poor ecosystem outcomes and RCI=0?) and an upper boundary condition (What x-value is associated with positive ecosystem outcomes and RCI=1?). Assuming a linear trajectory between these points, the RCI can then be calculated as follows:

$$ RCI = \frac{x - LB}{UB - LB} $$

where

- $x$ = Future without Project (FWOP) or Future with Project (FWP)
- $UB$ = Upper boundary condition for the RCI (i.e., best condition, RCI=1)
- $LB$ = Lower boundary condition for the RCI (i.e., worst condition, RCI=0)

Selecting Boundary Conditions for the RCI. Restoring urban ecosystems that were destroyed or subjected to anthropogenic physiochemical alterations for decades or centuries is a daunting, if not impossible, task. Consequently, given the aforementioned constraints and environmental stressors associated with urban streams, many of which are considered irreversible, the authors recommend construction of an RCI that is scaled against BAC within a given physiography, region, stream class, or land use. Stoddard et al. (2006) defined BAC as “the expected ecological condition of least-disturbed sites if the best possible management practices were in use for some period of time.” Achieving BAC is dependent on “convergence of management goals, best available technology, prevailing use of the landscape, and public commitment to achieving environmental goals.” Stoddard et al. (2006) defines the upper and lower limits of BAC as the minimally disturbed condition (MDC) and the least disturbed condition (LDC), respectively.

Selecting Ecosystem Attributes for the RCI. The RCI may be formulated relative to any locally meaningful ecosystem attribute (e.g., impervious area, nutrient concentration, etc.). Since numerous factors have negative consequences on the hydrology, geomorphology, and ecology of urban streams, the authors of this report suggest the use of indices that are representative of multiple pollutants, concentrated sources, and/or exert cumulative effects. For instance, water quality related to water chemistry generally declines with increasing percent impervious area (PIA) (Ourso and Frenzel 2003).

EXAMPLE APPLICATIONS OF THE RCI FOR URBAN STREAMS: Three case studies are presented below to demonstrate the application of the RCI. For each example project, a brief description of the ecological challenge is identified, an RCI is formulated using multiple assumptions, and a simple, hypothetical restoration scenario is presented. For each restoration scenario, the consequences of different RCI assumptions on the conclusions drawn for futures without and with restoration actions (FWOP and FWP, respectively) are examined.
Percent Impervious Area. In an urban setting in Anchorage, Alaska, Ourso and Frenzel (2003) identified a set of response variables related to percent impervious area (PIA) along a steep urbanized gradient over short distances. They observed a significant correlation between riparian and instream habitat, macroinvertebrate communities, and water/sediment chemistry relative to PIA. Contaminants such as salts, oils, and gasoline from roadway runoff, pathogens from wildlife and pets, and nutrients from fertilizers were identified as leading causes of ecological impairment. Using a sliding regression analysis of eight variables, a threshold response corresponding to a mean of 4.4 to 5.8 PIA was revealed, which is consistent with literature that reported impact thresholds in other systems of 4–5 PIA (May et al. 1997) and 10–12 PIA (Klein 1979, Booth and Jackson 1997, and Wang et al. 2000).

The RCI was constructed with two sets of assumptions (Figure 1). First, the upper and lower bounds were assigned to 0 PIA and 100 PIA, respectively, which assumes that ecological impact scales linearly as development increases. However, data presented by Ourso and Frenzel (2003) demonstrate that this assumption is null, and thresholds exist in both the initiation of impact and the maximum extent of impact. Using their findings, a second RCI was developed, which assigned the upper and lower bounds to 4.4 PIA and 40 PIA, respectively. These boundary conditions rely on regionally developed knowledge that a threshold in ecological impact occurs above 4.4 PIA and a maximum level of development occurs around 40 PIA (i.e., the most developed site in the Chester Creek watershed at Arctic Boulevard). The rescaling of the RCI to locally appropriate reference conditions led to a dramatically different quantitative basis for impact in this system.

![Figure 1](image-url)  
**Figure 1.** Multiple definitions of reference conditions associated with impervious area in urban streams of Alaska (Ourso and Frenzel 2003).

The effect of the competing RCI boundary conditions was tested with a simple restoration scenario where reforestation of riparian zones and greenways decreases PIA from an existing condition of 40 PIA to a restored condition of 20 PIA (denoted as FWOP and FWP, respectively). Using the
first formulation of the RCI (without local data), the change in RCI between the scenarios is a mere 0.20 (i.e., 0.80 for FWP and 0.60 for FWOP). Conversely, when including local knowledge of reference conditions, the change in the RCI is 0.56 (i.e., 0.56 for FWP and 0.00 for FWOP). As such, the net effect of restoration would be underestimated without changing the reference condition to a locally appropriate set of conditions.

**Nutrient Impairment.** Brett et al. (2005) analyzed a 10-year record on 17 streams in the greater Seattle, Washington region for stream nutrients and sediment concentrations. The drainages span from 22–87% urban or 6–73% forested land use. Most of the urban streams had 95% higher total phosphorus (TP), 122% higher soluble reactive phosphorus, and 71% higher turbidity as compared to the forested streams. From these data, the authors propose the following relationship between TP and percent forested area (Brett et al. 2005):

\[
TP \ (\mu g/L) = 83.3 - 0.687 \times \%\text{Forest}
\]  

(2)

The RCI was constructed with two sets of assumptions relative to total phosphorous (Figure 2). First, the upper and lower bounds were assigned to 0 and 100% forested land use (83.3 µg/L and 14.6 µg/L, respectively), which assumes that ecological impact scales linearly as development increases. However, equation 2 extrapolates beyond the range of observed land use conditions, and a second RCI was developed, which assigned the upper and lower bounds to 6% and 73% forest cover (79.2 µg/L and 33.1 µg/L, respectively). These boundary conditions rescale to regionally appropriate thresholds in land use conditions.

Figure 2. Multiple definitions of reference conditions associated with forest cover effects on TP in streams in urban Seattle, Washington (Brett et al. 2005).
The authors tested these RCI formulations for a restoration scenario doubling forest cover in riparian zones and greenways from 18% to 36% (FWOP and FWP, respectively), which corresponds to 70.9 µg/L and 58.6 µg/L. While the magnitude of change in phosphorous is the same (12.3 µg/L), the relative observation of change differs depending on the assumptions used in formulating the RCI. The RCI for the unscaled model changes from 0.18 to 0.36 (0.18 net), while the RCI for the locally rescaled model changes from 0.18 to 0.45 (0.27 net). Again, this analysis shows that without locally rescaling the RCI, the benefits of restoration may be underestimated.

**Chemical Impairment.** Nedeau et al. (2003) studied the effects of an industrial effluent on water and habitat quality on an urban stream in southwestern Michigan. Land use and cover in the watershed was predominantly urban (65–80%) and forested (5–15%) with wetlands and agriculture accounting for less than 10%. Increase in total discharge and flow from the industrial effluent did not adversely affect stream biota, but it improved species richness. However, ferric hydroxide precipitate from high iron concentrations in the effluent had a profound effect on the colonization and growth of periphyton, which includes an important primary food source for aquatic food webs. Total dissolved iron ranged from 0.046–0.121 mg/L upstream of the effluent to over an order of magnitude higher downstream (0.377–2.680 mg/L).

In this example, the RCI was constructed with two competing models (Figure 3). First, the upper and lower bounds were assigned from the range of the most disturbed upstream condition (0.121 mg/L) to the most disturbed downstream condition (2.68 mg/L), which implies assumptions about the best and worst attainable conditions in the watershed. Conversely, a second RCI was formulated to range from the most disturbed upstream condition (0.121 mg/L) to the least disturbed downstream condition (0.377 mg/L), which assumes that any effluent may be treated to the best industry level.

![Figure 3. Multiple definitions of reference conditions associated with effluent of total dissolved iron in southwestern Michigan (Nedeau et al. 2003).](image-url)
In this restoration scenario, the authors applied these competing RCI models to examine the application of advance treatment intended to reduce iron concentrations in the industrial effluent by 60% from 1.5 mg/L to 0.6 mg/L. The first RCI formulation resulted in a relatively large change in RCI of 0.35 (i.e., 0.46 FWOP and 0.81 FWP). However, the second model resulted in no change in the RCI (i.e., 0.00 FWP to 0.00 FWP). The reduced scale in the second model increases the burden of proof for the industrial discharge, and thus leads to a dramatically different conclusion regarding the level of efficacy of the water treatment action.

DISCUSSION AND CONCLUSIONS: The history of anthropogenic impact varies significantly in its timing and intensity between urban settings, watershed land use, stream types, as well as between different kinds of human activity. Paramount to restoration of urban streams is assessment of contemporary conditions, historic trends, and establishment of a range of reference conditions, which are, in many cases, stream segment dependent. Establishing a suite of reference conditions that span from highly disturbed to the minimally disturbed condition by constructing an RCI provides a means of identifying achievable restoration targets in urban streams.

The proposed RCI approach proposed and demonstrated here provides a defensible mechanism for rescaling restoration outcomes appropriately for altered urban conditions. The approach has been shown adaptable for a variety of ecosystem attributes (e.g., impervious area, total phosphorous, total dissolved iron) and flexible to targets specified by a restoration team (e.g., different upper and lower bounds). Furthermore, the RCI provides a consistent scale (0 to 1) for communicating the relative benefits of restoration actions to project partners, decision makers, and stakeholders. However, the selection of attributes and boundary conditions is non-trivial and should be done in conjunction with the best available regional science as well as the explicit participation of team members. Without either of these factors, the increase in understandability provided by the RCI could be overshadowed by disagreement over the assumptions used in its development.

Even in urban settings, aquatic ecosystems are not static but vary naturally on short (interannual to decadal) time scales and undergo change on longer (centennial to millennial) timescales due to both autogenic processes and natural exogenous forcing (Deevey 1984). Of greater concern is the future impact of climate change, which has the potential to modify the fundamental behavior of freshwater ecosystems to a point where a historical reference state can no longer be a realistic target for recovery (Battarbee et al. 2005).

Future research and development should focus on the following needs: (1) establishing an appropriate classification system for urban streams or set of systems to support reference-based restoration and benefits assessment, (2) determining which attributes are appropriate for each ecosystem class, so that assessments can be reasonably comparable, (3) developing detailed guidance for selecting reference conditions, and (4) formulating regional reference indices that capture the natural range of ecosystem-specific variability within a given ecoregion or hydro-physiography.

ADDITIONAL INFORMATION: Research presented in this technical note was developed under the Ecosystem Management and Restoration Research Program (EMRRP). The U.S. Army Corps of Engineers (USACE) proponent for EMRRP is Ms. Mindy Simmons and the Technical Director is Dr. Al Cofrancesco. Technical review was provided by Chris Noble.
For additional information, contact Bruce A. Pruitt (706-355-8121), or the manager of the Environmental Benefits Analysis Research Program, Dr. Trudy J. Estes (601-634-2125), Trudy.J.Estes@usace.army.mil. This technical note should be cited as follows:


REFERENCES


*NOTE: The contents of this technical note are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such products.*