Research Needs for Improvement of Principles and Practices in Urban Stream Restoration

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Abstract

Restoration of urban streams requires unique approaches because human activities associated with urban development permanently alter a stream's hydrology, geomorphology, water quality, and ecology from its original "natural" state. It is well understood that the return to a pristine condition is not possible for many urban streams. It is less understood how in urbanizing streams the changes in fundamental watershed processes result in physical and biological degradation. The urban condition imposes many constraints to a restoration effort complicating design process that must consider the protection of infrastructure, pollutants associated with stormwater runoff, and hydromodification that changes over time as more development increases impervious land surfaces. A natural channel design approach is commonly used in urban streams, though some practitioners question whether such an approach is appropriate bearing in mind the potential urban constraints. At a minimum, advanced approaches in combination with the natural channel design approach are needed, including: improved classification and assessment techniques of watersheds and streams that identify physical, chemical and biological metrics relevant to the urban condition, use of engineering hydrology, hydrodynamic, and sediment transport models that can forecast changes in discharges and channel morphology over time, improved design guidelines for instream improvement structures, a planning processes that embraces the human element through stakeholder involvement, and an overall design methodology that is habitat-based and watershed process-orientated. Within the limits of information gathered, this paper summarizes some current research, as well as critical knowledge gaps, related to urban stream restoration. Ultimately, the authors hope it facilitates an active exchange of ideas among colleagues involved in improving restoration principles and practices in urban streams.

Introduction

The need to distinguish urban stream restoration from general approaches in restoration is evident by how dramatically human activities permanently change the fluvial system within an urban watershed. In fact, stream restoration as defined by the National Research Council (1992), as “a return of an ecosystem to a close approximation of its condition prior to disturbance”, is simply not possible in urban watersheds. Because of the common use of the term “stream restoration” in the engineering practice, we use it here understanding that the urban condition limits what can be achieved with the return of natural ecosystem function.

Other definitions are more appropriate to restoration efforts applied to urban streams, such as naturalization (Rhoads and Herricks 1996) and rehabilitation (Booth et al. 2001). These definitions explicitly identify two important design objectives as ecosystem enhancement and socioeconomic acceptance by local stakeholders. Ecosystem enhancement is essential to meet the basic intent of the Clean Water Act of 1972, as promulgated in Section 101, where its directive is to “restore and maintain the chemical, physical, and biological integrity of the Nation’s waters.” Much progress has been made to meet these goals since the Act’s authorization, but achieving chemical, physical, and biological integrity in urban streams is a difficult problem due to the detrimental and permanent impacts to stream quality. The USEPA (1995) has provided some guidance on ecological restoration, but lacks a design framework specific for urban stream restoration. A design framework for urban stream restoration must embrace the notion that conceptions of “natural” are community-based and place-specific (Rhoads et al. 1999). What a community perceives as “natural” becomes the restoration design end point. Involvement of a community with project planning and design enhances their awareness and ownership of the stream, promoting local activities that reduce sources of non-point pollution. Importantly during a project’s design, involvement must consist of an accurate technological transfer from the design team to the stakeholders. This is somewhat problematic at present, since a scientific and engineering basis for urban stream restoration founded on chemical, physical, and biological processes does not exist (Hession 2001). Current research is improving our understanding of these fundamental processes in modified, urban streams. The ultimate goal of research is to develop a restoration design framework specific to the urban condition accounting for long-term channel dynamics, community social values, and ecological integrity.

The purpose of this paper is to discuss, from a scientific and engineering basis, what distinguishes the principles and practices of urban stream restoration from those adopted for rural streams. This paper characterizes the urban stream condition in order to distinguish critical research needs for improvement of urban stream restoration principals and practices. It also addresses the significant challenges of improving urban watershed analysis and planning techniques. This paper is not intended to be a comprehensive summary of the topic, but rather an initial step to identify critical research needs for urban stream restoration design, in order to promote discussion of this subject.

The Urban Stream Condition

Hydrology, geomorphology, water quality, and ecology can be permanently altered in an urban stream. Direct hydrologic modification by urban development includes reduction of baseflows from water supply diversions, which reduce useable habitat for aquatic organisms, and in some locations increased baseflows from sewage effluent discharges. Channel morphology can be directly modified from new infrastructure construction, such as roads, bridges; culverts, sanitary and utility pipelines; small dams; and flood control levees. In many cases, the morphological character of the channel becomes simplified as a result of these construction activities, such as straightening, grading bank slopes, and removing large woody debris. Construction activities may incorporate hydraulic controls, planned or unplanned, that fix lateral and/or vertical control points. These fixed hydraulic control points prevent a stream to function in stable morphological condition, known as a state of "dynamic equilibrium", but rather shift streams to a condition of rapid morphological adjustment. Indirectly, hydrologic and morphological modifications occur from increased impervious land surfaces in a watershed. Studies have shown that a ten percent increase in watershed imperviousness can modify the hydrologic regime (Booth and Jackson 1997; Bledsoe and Watson 2001; CWP 2002). Hydrological changes include storm flows with greater peaks and runoff volumes that cause channel enlargement by incision and widening through accelerated bank erosion. In humid regions, baseflows are not sustained during summer periods because of a reduction of groundwater recharge.

With these hydrological modifications also come changes in sediment transport dynamics and streambed size-class properties (MacRae 1996). Sediment yields in urban streams are impacted by excessive soil loss from poorly applied erosion control measures during land development, and reduction of sediment storage capacity by eliminating floodplains. These changes in sediment dynamics can cause rapid adjustment of channel morphology, thereby degrading physical habitat. Observable changes in channel morphology and stream habitat may lag many years from initial development in a watershed and continue for years after complete development with highly impervious land uses (Fischenich 2001).

Water quality in urban streams is impacted from pollutants associated with stormwater runoff, in which non-point source pollutants increase from human activities including automobile use, oil spills and dumping, and overuse of lawn and garden chemicals (Urbonas 2001;CWP2002b; CWP2003). Pollutants consist of excessive nutrients, sediment, and toxins. These pollutants enter urban streams rapidly due to lack of stormwater retention, particularly in older developed areas pre-dating stormwater regulations. Stream temperature can increase from stormwater runoff entering channels flowing over heated pavement, discharges from extended detention ponds, and tree removal in the riparian corridor (ul Hag and James 2002). Poor water quality reduces the biological diversity in these streams, and in extreme cases, urban streams may be void of larger aquatic species. Degradation of stream ecological integrity from urbanization is complicated from the multitude of possible and interacting impacts, including poor water quality and physical habitat together, which changes gradually over time (Kondolf 1995).

Classification and Assessment of Urban Watersheds and Streams

Classification of urban watersheds and streams of current condition is possible, but assessment is more problematic because of the interacting and dynamic environmental factors of the urban condition, absence of relevant reference sites, and lack of good historical data limit our predictive ability. In general, classification of watersheds and streams is based geomorphic characteristics, geology, and physical habitat structure (Montgomery and Buffington 1993; Rosgen 1996; Raven 1998; Frothingham et al. 2002). Classification is hierarchical and organized into different scales, for example, valley types, channel reaches, pool-riffle bedforms, and bed material. Various assessment overlays include vegetative cover, and current and future land use. Classification provides the necessary interpretative data for assessment, and planning of corrective measures.

Geomorphic characterization is a necessary component to classification and assessment, but water quality and ecological data are also needed to assess the urban stream condition. Important questions remain, for example what fluvial processes maintain habitat quality in urban systems with modified sources and transport rates of sediment. The geomorphic classification system developed by Rosgen (1996) is widely used to characterize rural streams and initiate stream restoration design; however proper use of this technique in urban streams has been a debated (Miller and Skidmore 2001; Callahan 2001). The Rapid Stream Assessment Technique (RSAT) developed by the Center of Watershed Protection (1999) uses a qualitative procedure to assess stream condition that include the following categories: 1) channel stability, 2) channel scouring and sediment deposition, 3) physical instream habitat, 4) water quality, and 5) riparian habitat, and 6) biological indicators (macroinvertebrates). Another assessment framework that includes physical habitat, water quality, and biological protocols was developed by the Nottawasaga Valley Conservation Authority (www.nvca.on.ca) that include 1) biological protocols [BioMAP, Rapid Bioassessment Protocol, Index of Biotic Integrity]; 2) diagnostic habitat and water chemistry protocols [stream habitat surveys, water chemistry sampling]; and 3) toxic contaminant protocols [toxics sampling]. More research is needed to improve the classification and assessment of urban watersheds and streams that provide a better link between ecological degradation and physical-chemical stressors.

Comprehensive assessment protocols must be integrated with a vulnerability analysis identifying potential impacts to the streams, which then can be used to prioritize restoration measures for watershed management and planning (CWP 2002a). The Center for Watershed Protection developed an analysis, in which urban watersheds are primarily assessed on basin size and percent impervious cover. Other assessment data in their analysis include: land use area by zoning, future impervious area based on land use plans, downstream water resources, stream mileage, percent mileage in forested corridor, existing forest cover, existing jurisdictional wetlands, amount of developable land available, road crossing, NPDES discharge permits, and existing and planned sanitary sewers. These data are essential information to an urbanizing watershed, particularly in large urban metropolitan areas because streams in these areas are most vulnerable to chemical, physical and biological changes from development. Overall, improved protocols for classification and assessment of urban watersheds and streams will contribute to more effective management and planning.

Urban Watershed Management and Planning

Watershed management and planning techniques in urban environments are implemented at three restoration scales (USEPA 1995). They are: 1) *upland and watershed techniques*: related to the control of non-point source inputs from best management practices (BMPs), including hydrological runoff characteristics from increased impervious surfaces; 2) *riparian techniques*: re-establishment of native vegetative canopy in the riparian corridor; and 3) *instream techniques*: applied directly to the active channel restoring planform and hydraulic geometry, bank stability, and morphological complexity of the streambed. Implementation of the watershed techniques is greatly influenced by the need to mitigate hydrologic modifications and water quality problems. Stormwater management programs must be integrated with overall watershed management strategies to address these problems. Complexity of the urban problem has been observed from case studies where after implementing stormwater BMPs urban streams remain degraded (Urbonas 2001). Research continues to improve the effectiveness of stormwater BMP design, and the performance on impact mitigations to urban streams.

Riparian and floodplain areas are threatened in urban watersheds from development pressures, and need protection and conservation through management and planning. Research has defined criteria for when riparian buffers are effective and required in urban areas, and it has also prescribed variable buffer widths based on site condition or need (Leavitt 1998; Wenger 1999; ASCE BMP Committee 2001; Quinn et al 2001). Some municipalities establish buffer requirements based on stream classification (perennial streams are buffered, intermittent streams are not), while others use total drainage area at a point (greater than one square mile drainage area has a buffer requirement, less then one square mile drainage area does not), or special needs of the community and *green* value (Chase et al. 1995). Studies have been conducted on floodplain roughness to better understand the special role of riparian vegetation in flood events (Fathi-Moghadam and Kouwen 1997). Recently, D'Antonio and Meyerson (2002) have examined the control and/or elimination of exotic invasive species in ecological restoration projects.

Urban project planning for instream techniques must be integrated with watershed and riparian techniques through socioeconomic considerations that include land values, urban renewal, riverfront access, flood control, recreation, linear greenways, aesthetics, and habitat enhancements (Streiner and Loomis 1997; JAWRA 1999; Purcell et al. 2002). A new attitude emerging among urban water managers is that a marriage between technical solutions and public input is a key factor in project success (Brooks and Palmer 1999; Wade et al. 2002). Accommodating a wide range of interests among stakeholders may be one of the biggest challenges in implementing watershed restoration/protection efforts (Eden et al. 2000). Being able to integrate complex technical, legal, and economic issues is imperative, particularly when engineering design criteria is needed to reduce a level of uncertainty because project failure from property damage is very costly. Local watershed councils are a key driving force in the integration of technical and socioeconomic issues. The most successful watershed councils tend to have voluntary cooperation, consensus decision-making, and flexibility in organizational structure and problem solving efforts (Kenney 1999). More research is needed to improve methods of technical transfer to the stakeholder from scientists and engineers, particularly with the exchange of complex assessment and planning strategies. It is more imperative today, because stakeholders have easy access to information on channel restoration design approaches, but may lack technical skills to appropriately install instream improvement structures.

Natural Channel Design Approaches in Urban Streams

Watershed groups, government agencies, and consultants have moved towards stream restoration designs that simulate "natural" conditions, commonly known as the natural channel design approach. Stakeholders value streams that appear more "natural", and seldom accept traditional engineering designs emphasizing trapezoidal or rectangular sections with rigid armored boundaries. The negative impacts from this past design approach on aesthetics, recreation, property value, and ecological health have been well documented in urban streams (Purcell et al. 2002).

Common practice for natural channel design approach combines the use of empirical relationships from geomorphic principles and reference site conditions to support designs aimed at restoring channel stability (Brooks and Sear 1996; Rosgen 1996; FISRWG 1998; Hey 2002; Heaton et al. 2002; ACB 2003). This approach is based on two main assumptions 1) channel dimensions based on hydraulic geometry relationships will create stable channels, and 2) stable channels provide for higher quality habitat supporting healthy ecosystems (Brown et al. 2002). Natural channel design approaches use detailed physical surveys of a reference reach and the impacted stream reach, and nearby flow gauging station data. The data are used to apply the Rosgen (1996) technique, in which channel geomorphic types are classified, and hydraulic geometry variables are computed for design. Design parameters include meander pattern, floodplain width, width and depth of a bankfull channel, riffle spacing, and slope based on dimensionless ratios taken from a stable reference reach located in the same hydrophysiographic region. The area and discharge of the bankfull channel are based on the existing conditions survey, and validated using regional curves. Mean velocity measurements are used in simplified entrainment calculations. Most natural channel design methods provide multiple levels of channel stability analysis. A more advanced stability analysis uses the Pfankuch method to evaluate channel stability qualitatively from field observations and a bank erosion hazard index (BEHI) analysis to estimate bank erosion rates (Rosgen 1996).

In many urban streams, this common practice of natural channel design is difficult to apply, or may simply be inappropriate considering how the urban condition can affect design parameters. For example, bankfull channel dimensions are not in equilibrium with an "effective" discharge, but enlarge over time as urban development increases stormwater runoff rates. Infrastructure issues must be considered, since channels with mobile boundaries are not desirable near bridges, buildings, and utilities. Also, the cost of development removal can be prohibitive, and simply may not be a socially acceptable alternative in many communities. A key issue with the natural channel design approach is that a reference condition is of limited use for urban steams with dynamic hydrologic and sediment regimes, and morphologies controlled by local infrastructure. Application of regional hydraulic geometry curves that are based on rural stream data is not an acceptable practice. Regional curves developed specifically for urban streams are just emerging (Doll et al. 2002), but in general more research is needed (Wilkerson 1998; Brunner 1999), including the use of a confidence interval or some measure of uncertainty in the design computations (Johnson and Heil 1996). Restoration design priorities in urban streams must be modified considering the constraints imposed by the urban condition (Rosgen 1997; Doll et al. 2002); and they have been organized as follows: 1) re-establish the channel on its previous floodplain, 2) re-establish the channel and floodplain at the stream's existing elevation, 3) covert stream types without creating an active floodplain, and 4) stabilize the channel in place. Further research is needed to clarify how key watershed conditions, such as impervious land cover, time since development, and hydrological connectivity, influence restoration designs in urban stream channels.

Technological advancements are needed to improve upon the channel stability practices used for the natural channel design approach in urban streams (Fischenich 2002). Advancements include the use of deterministic modeling tools in engineering hydrology, hydrodynamics, and sediment transport. Hydrologic models can forecast future flow characteristics rather than relying on past flow data or bankfull indicators. These models determine water profiles for potential flood frequencies under built-out conditions in a watershed, and are necessary to insure public safety. Restoration approaches that combine geomorphic and engineering methods to design and construct geomorphologically sound stable channels have been utilized to some extent (Brookes 1988; Newbury and Gaboury 1993; MacBroom 1998; Soar and Thorne 2001). This urban restoration approach begins with use of reference reaches, if available, and regime equations to set trial dimensions for the main channel bankfull width and depth. It then uses a non-uniform flow, one-dimensional hydrodynamic model (i.e., HEC-RAS) to determine water profiles and evaluate supplemental floodway or floodplain flow capacity needs. Channel stability is then checked with empirical relationships between critical shear stress and mean particle diameter, where a threshold velocity or shear stress is computed from mean velocities at bankfull discharge. Research on the use of dynamic sediment transport models would greatly aid in predicting long-term stability of channel designs and instream improvement structures.

One criticism of the natural channel design approach is that once the basic channel dimensions have been determined, minimal engineering criteria exist to aid practitioners in the selection and design of instream structures. Many types of improvement structures have been used in urban streams (Brown 2000). They include hydraulic grade and flow controls (e.g., rock vortex weir, rock cross vane or alternating single wing deflectors, double wing deflector, log drop/sill and V-log drop, log vane, and cut-off sill), and bank stabilization/ protection structures (e.g., rootwad revetment, imbricated rip-rap, boulder revetment, A-jacks, and coir fiber logs) (Rosgen 1996; Heaton et al. 2002). Choice of instream improvement structures for a restoration project is commonly based on popularity and familiarity (Walsh 2002). The design focus has been on placement of in-channel "natural" features rather than fluvial and ecological processes. General construction guidelines are available by some state and local agencies such as Georgia, North Carolina, Maryland, Pennsylvania, Oregon, and Washington. Research is needed to evaluate the performance of these structural practices in order to improve existing construction guidelines. Recent progress has been made where Johnson and others (2002a) examined design of in-channel structures near bridges. Their research evaluated the effectiveness of vanes, cross-vanes, and w-weirs for preventing scour at bridge abutments and suggested optimum design parameters based on laboratory experiments that could also be used in restoration projects. Improved design criteria of these structures based on hydraulic research must include variables related to dominant and/or peak discharges, sediment transport capacity and rates, bed sediment and bank soil properties, and complexity of morphological settings.

In addition, Johnson and others (2002b) recommend that an adaptive management strategy be applied to improve these design guidelines through more effective post-construction monitoring and greater sharing of data among the professional community. Few post-construction monitoring studies have been published on the performance of instream structures for use in urban streams. One such study by Brown (2000), urban stream restoration projects were evaluated on 22 commonly used structural practices. This study found that nearly 90% of the structures evaluated remained structurally intact after an average of four years, though 20 to 30% had varying levels of unintended sediment scouring or deposition. Project failures were caused by inappropriate channel conditions for the prescribed practice, improper project design, and/or poor construction. When habitat enhancement was considered, less than 60% of the projects fully met their intended objectives. This finding illustrates that very little is understood about how habitat and ecological processes relate to geomorphic-based designs.

Development of design protocols that integrate ecological criteria is critically needed for natural channel design approaches. Incorporating ecological criteria from pre-construction bioassessment data into the initial design stages can provide for proper selection and design of habitat enhancement structures. Ecological benefits may be derived for non- traditional channel structures, such as large woody debris, in urban streams (Larson et al. 2002). From a design perspective, hydrodynamic and sediment transport models can be useful engineering tools in the analysis of habitat quality and long-term maintenance. In a recently completed stream restoration project in the Chicago, Illinois metro area, geomorphic, hydraulic, and ecological criteria were integrated in the initial design stages (Rodríguez et. al. 2000; Schwartz et. al. 2002). Significant ecological improvements have been observed as a result of this project. Overall, an ecological design framework for urban stream restoration should be process-orientated and habitat-based (Booth et al. 2001; Schwartz et al. 2001; Schwartz 2002).

Ecological Health in Urban Streams

Improvement of ecological health of an urban stream cannot always be assumed through the implementation of a natural channel design approach. Recent results evaluating the ecological success of restoration practices have been mixed, ranging from increased fish and macroinvertebrate densities (Moerke and Lamberti 1999) to reduced biodiversity in restored areas (Jack et al. 2002; Pike et al. 2002). Walsh and Breen (1999) found similar conflicts in ecological responses to urban stream restoration practices in Australia. Interestingly, they found that water quality, particularly high biochemical oxygen demand, had a more direct effect on the macroinvertebrate community than physical habitat quality. This finding emphasizes the overall need to assess both chemical and physical degradation prior to restoration planning and design. A broad, watershed view is needed in urban stream restoration to address potential impacts related to water quality, physical habitat, or both.

Ultimately the true measure of success in stream restoration is how the aquatic community responds to the applied treatments.

Complex relationships between physical habitat structure and ecological integrity are not well understood in urban streams. A few studies have been conducted in this area. Booth and others (2001) document consequences of urban development on stream morphology, habitat, and biotic community in urban streams in the Pacific Northwest, and begin to address issues related to the fundamental geomorphic, hydraulic and ecological processes that influence physical and biological degradation. Hession (2001) investigated the role of riparian forest corridors in maintaining ecological health of urban streams. Other research has included "developing an improved method for designing and optimizing environmental flow" by identifying hydraulic flow events that trigger key ecological processes and link them to specific biological processes or the life-cycles of organisms (Walsh 2002). Examples of such events include periods when: 1) bed sediments are mobilized, 2) large woody debris and backwaters are inundated, 3) the streambed is exposed, and 4) benches and the floodplain are inundated. Overall, a wide range of research is needed in this area, including the development of habitat-based design criteria through the integration of geomorphic, hydraulic, and ecological principles (Schwartz 2002); and standardization of pre-construction biomonitoring protocols relevant to the urban stream (Bash and Ryan 2002).

Summary Points: Critical Research Needs

This review of current principles and practices for urban stream restoration, and associated research underscores several critical research needs. We summarize those research needs as follows:

1) Improved understanding of fundamental geomorphic, hydraulic and ecological processes that influence physical and biological degradation in urbanizing streams;
2) Improved classification and assessment protocols of watershed and streams that account for the urban condition recognizing the influence of water quality, physical habitat degradation, and a stressed ecosystem;
3) Improved watershed management and planning methods that assesses vulnerability from urbanization through process-orientated "threshold" metrics that better predict impacts to hydrology, channel and planform morphology, physical habitat, water quality, and ecology;
4) Development of regional hydraulic geometry equations specifically for urban streams, and also define the range of uncertainty in the relationships;
5) Improved engineering design criteria for use of instream structures based on a relevant characterization of channel stability for the urban condition;
6) Advancement of restoration design methods through use of multidimensional hydrodynamic models, dynamic sediment transport models, and habitat models;
7) Development of a restoration design framework for instream structural practices that integrates geomorphic, hydraulic, and ecological processes; and
8) Improved pre- and post-construction monitoring protocols of the stream condition, including measures of channel stability, physical habitat, and

biological integrity, in order to compare with traditional restoration practices, and verify their long-term performance.

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