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FEATURE

A Review of Urban Water Body Challenges and Approaches: (1) Rehabilitation and Remediation

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ABSTRACT: *We review how urbanization alters aquatic ecosystems, as well as actions that managers can take to remediate urban waters. Urbanization affects streams by fundamentally altering longitudinal and lateral processes that in turn alter hydrology, habitat, and water chemistry; these effects create physical and chemical stressors that in turn affect the biota. Urban streams often suffer from multiple stressor effects that have collectively been termed an "urban stream syndrome," in which no single factor dominates degraded conditions. Resource managers have multiple ways of combating the urban stream syndrome. These approaches range from whole-watershed protection to reach-scale habitat rehabilitation, but the prescription must be matched to the scale of the factors that are causing the problem, and results will likely not be immediate because of lengthy recovery times. Although pristine or reference conditions are far from attainable, urban stream rehabilitation is a worthy goal because appropriate actions can provide ecosystem improvements as well as increased ecosystem service benefits for human society.*

Revisión de Enfoques y Retos en el Estudio de Cuerpos de Agua Urbanos: (1) Rehabilitación y Remediación

RESUMEN: *se hace una revisión de cómo la urbanización altera los ecosistemas acuáticos, así como también de las acciones que los administradores pueden tomar para remediar el problema de las aguas urbanas. La urbanización afecta los ríos a través de la alteración de procesos longitudinales y laterales que, a su vez, modifican la hidrología, hábitat y química del agua; estos efectos crean factores químicos y físicos de estrés que perturban la biota. Los ríos urbanos suelen estar sujetos a múltiples factores de estrés que colectivamente se conocen como "síndrome del río urbano" en el cual no existe dominancia de un solo factor de degradación. Los administradores de recursos naturales tienen diversas formas de combatir este síndrome. Estos enfoques van desde protección de cuencas enteras hasta rehabilitación de hábitats a gran escala, pero la prescripción debe ser consistente con la escala de los factores que están causando el problema, y es probable que los resultados no sean inmediatos dado que los tiempos de recuperación son prolongados. A pesar de que se está lejos de poder reconstruir las condiciones prístinas o de referencia, la rehabilitación de los ríos urbanos es un objetivo digno de perseguir ya que la toma de acciones adecuadas pueden lograr mejoras a los ecosistemas así como también un incremento en los beneficios que la sociedad humana obtiene de ellos.*

PREFACE

This article and its companion (Hughes et al., 2014) stem from two reports published by Oregon's Independent Multidisciplinary Science Team (IMST 2010, 2012). The IMST was established by Oregon Revised Statute 541.409 in 1997 to provide independent, impartial advice to the state on scientific matters related to the Oregon Plan for Salmon and Watersheds. Previous IMST reports and agency reviews had focused on forest and agricultural land uses, and most of the rehabilitation efforts in the state were focused on those landscapes because of their great extent. The IMST recognized, however, that (1) most Oregon citizens live in cities and rural residential areas, (2) many important salmonid streams and rivers pass through those urban areas, and (3) urban areas play a key role in salmonid rehabilitation. Therefore, IMST (2010) was written to evaluate the science and how actions in urban and rural residential areas might aid salmonid recovery and catchment condition. Following completion of IMST (2010), the IMST held a workshop composed of municipal and state environmental managers and practitioners in 2011 to help fill gaps existing between the published scientific literature and what is known and needed by professionals actively working to rehabilitate aquatic resources in Oregon urban and rural residential areas. IMST (2012) summarized what was learned at that workshop and stimulated these two *Fisheries* articles, as well as a book (Yeakley et al., 2014).

INTRODUCTION

Human societies alter water bodies, the effects of which are dependent on the relative sizes of the urban centers versus the water bodies, their industries, and the natural and historical setting of the city. Because most people now live in cities and water is critical to human health and well-being, it is vital to maintain water quality in socially, economically, and ecologically effective ways. Although ecological effects of urbanization on aquatic ecosystems are described well in the scientific literature, approaches for rehabilitating and mitigating problems have received less attention and have not been considered in a practical, integrated manner. We review and summarize various approaches for reducing the effects of current urbanization on surface waters and discuss their benefits and limitations. Our review is divided into two major sections: (1) effects of urbanization on aquatic ecosystems and (2) actions for rehabilitating aquatic ecosystems in existing urban areas.

Urbanization results in a phenomenon commonly known as the "urban stream syndrome," whereby hydrographs become flashier (i.e., increased flow variability), water quality is degraded, channels are homogenized and incised, biological richness declines, and disturbance-tolerant and alien species increase in prevalence.

EFFECTS OF URBANIZATION ON AQUATIC ECOSYSTEMS

Understanding the effects of urbanization, or any land use, on aquatic ecosystems requires consideration of local- and catchment-scale effects, as well as current and historical effects. Civilizations began with cities around 9,000 YBP in the Middle East and China and 3,000 YBP in Mesoamerica. Many were hydraulic societies that modified their aquatic systems. This review, however, focuses on cities developing within the past 200 years. With over 50% of the world's population living in cities, and trending higher, urbanization is a global phenomenon (United Nations Population Division 2006; Grimm et al. 2008); 80% of U.S. citizens live in urban areas (Coles et al. 2012). High urban population density reduces the transportation cost of goods and services, offers greater employment opportunities, and increases information exchange that supports education and cultural enrichment (Grimm et al. 2008). However, urban areas fundamentally alter aquatic ecosystems—especially their hydrology, water quality, physical habitat quality, hydrological connectivity, ecological processes, and biota (Paul and Meyer 2001; Brown et al. 2005; Walsh et al. 2005; Chin 2006; Kaye et al. 2006; IMST 2010; R. A. Francis 2012; Yeakley et al., 2014). These multifactor stressors and complex ecosystem responses are called "syndromes" (Rapport et al. 1985; Regier et al. 2013). Urbanization results in a phenomenon commonly known as the "urban stream syndrome" (Walsh et al. 2005), whereby hydrographs become flashier (i.e., increased flow variability), water quality is degraded, channels are homogenized and incised, biological richness declines, and disturbance-tolerant and alien species increase in prevalence. This syndrome may begin under even low levels of disturbance; for example, Stanfield et al. (2006) and Stranko et al. (2008) found that only 4%–9% impervious catchment cover sufficed to eliminate salmonids from Ontario and Maryland streams. Residential development also simplifies the riparian and nearshore zones of lakes by installing retaining walls and by reducing riparian vegetation, shoreline complexity, and snags (Jennings et al. 1999, 2003; T. B. Francis and Schindler 2006), which in turn alter fish and macroinvertebrate assemblages (Whittier et al. 1997; Jennings et al. 1999; Brauns et al. 2007). Watershed damage occurs because urbanization alters catchment hydrology (Groffman et al. 2003; Walsh et al. 2005), soil conditions (IMST 2010), vegetation composition and cover (Booth et al. 2002), atmospheric chemistry (Kaye et al. 2006; Grimm et al. 2008), elemental mass balances and cycling (Groffman et al. 2003; Hook and Yeakley 2005), and riparian corridors (Bryce et al. 2002; Hennings and Edge 2003; Ozawa and Yeakley 2007). These alterations result in an urban land syndrome with simplified, compacted, and more mineralized soils having lower water retention capability, increased atmospheric deposition of pollutants, and replacement of natural vegetation structure with anthropogenic structures and impervious surfaces, culminating with replacement of native biota by alien taxa tolerant of anthropogenically altered ecosystems (Grimm et al. 2008). In nine cities studied by Coles et al. (2012), these terrestrial changes consistently resulted in loss of sensitive taxa, beginning at the earliest stages of urbanization (i.e., no resistance to low levels of development). Biological degradation continued at the highest levels of urbanization studied (i.e., no exhaustion threshold), suggesting that resource managers could obtain biological benefits from any appropriate rehabilitation and mitigation measures no matter the extent of catchment urbanization.

Cities often are located on floodplains, commonly at stream junctions; therefore, engineering approaches that minimize flood effects and maintain water supplies have been ubiquitous. Thus, basin-scale flood control and water supply projects are common. Impoundments designed to capture seasonal runoff and deliver water during the dry season or to produce hydropower are often located hundreds of kilometers upstream of urban areas. Such reservoirs homogenize flow regimes, simplify geomorphology, modify stream temperatures, and disrupt processes that deliver sediment and large woody material. They also disturb fish migration timing and behavior via barriers and provide refuges for alien invasive species (Columbia Basin Fish and Wildlife Authority 1991; Ligon et al. 1995; Williams et al. 1996). Frequently, river and stream banks both far from and within cities are channelized, rip-rapped, or leveed to speed water conveyance, limit channel movement, and aid navigation (Sedell and Froggatt 1984; Florsheim et al. 2008). Such changes can impair aquatic vertebrate and macroinvertebrate assemblages far from the impoundments and channel alterations (Poff et al. 1997).

Many current urbanization conditions are affected by historical land and water uses, particularly agriculture and channel alterations. Aboriginal humans altered natural flora and fauna through harvest, fire, and agriculture, and they also built canals and ditches that likely altered aquatic biota locally (Denevan 1992, 2011; Delcourt and Delcourt 2004). Intensive hydraulic engineering projects existed centuries ago in the Americas (Marsh 1976; Helfman 2007; Walter and Merritts 2008) and millennia ago in Europe (Quintela et al. 1987) and Asia (Temple 2007). Thus, the landscapes upon which many cities are built already had been transformed by prior land uses (Harding et al. 1998; Van Sickle et al. 2004; Brown et al. 2009). However, urbanization stresses stream ecosystems to a greater degree than most types of agriculture (Steedman 1988; Wang et al. 2000; Rawer-Jost et al. 2004; Trautwein et al. 2011; Ligeiro et al. 2013). In any case, cumulative effects of land cover changes, from natural vegetation to agriculture to urban, reduce the capabilities of streams to support their native biota (Stanfield and Kilgour 2006; Stanfield and Jackson 2011; Stanfield 2012).

Since the industrial revolution, effects of urbanization accelerated, intensified, and became much more extensive (Petts 1989). Many urban streams now occur only within underground pipes or concrete canals. Urban rivers are typically channelized, rip-rapped, and leveed; littoral zones of residential lakes now have shorelines converted to docks or retaining walls; and once-dense riparian forests are converted to park-like savanna. Navigable estuaries are regularly dredged, with shoreline wetlands converted to wharfs, seawalls, and commercial enterprises. For many urban dwellers these highly altered waterscapes form their images of a typical stream, river, lake, or estuary because they are founded on what they first experienced as youths or they are the only aquatic ecosystems they know (Pauly 1995; Figure 1). However, professional fisheries biologists, aquatic ecologists, and conservationists have different images and expectations for water bodies because of the many ecosystem services they provide (Costanza et al. 1997; Ervin et al. 2012). So what can we do about it? We offer a how-to approach based on identifying root causes and their scale.

REHABILITATING EFFECTS OF EXISTING URBAN AREAS ON AQUATIC ECOSYSTEMS

In this section, we first discuss the general goals of rehabilitating aquatic ecosystems and the limitations of doing so. These limitations include the many existing physical and chemical constraints resulting from urban infrastructure, the complex interwoven types of urban pressures, and the site-scale versus catchment- or basin-scale approaches for rehabilitation. We then discuss four major rehabilitation approaches: reestablishing natural land cover, wastewater and stormwater management, recovering hydrological connectivity and geomorphic complexity, and, finally, small-scale approaches such as bank stabilization (Table 1; IMST 2010).

Figure 1. Top: Amazon Creek, Eugene, Oregon; bottom: Townline Lake, Clare County, Michigan.

The Goal Is to Restore Processes, Not Specific Habitats

The typical objective of most rehabilitation projects is short-term physical habitat improvement. However, the primary goal of restoration is not to jump in and create a habitat but to regain historical ecological structure by naturalizing ecosystem processes that support stable flow regimes, instream habitat connectivity, riparian vegetation, and water quality (Roni et al. 2002; Beechie et al. 2008). An additional goal is to make waters safe for body contact as prescribed by the Clean Water Act in the United States (U.S.C. 33 § 1251) or the Water Framework Directive in the European Union (European Commission 2000).

Of course, in most urban areas, natural processes are highly constrained by infrastructure (Carpenter et al. 2003; Booth 2005; Bernhardt and Palmer 2007), pollution sources (Paul and Meyer 2001), and substantial geomorphic alterations (Jennings et al. 1999, 2003; Brown et al. 2005; Walsh et al. 2005; Chin 2006; T. B. Francis and Schindler 2006; Kaye et al. 2006; R. A. Francis 2012). Consequently, aquatic ecosystems in urban areas cannot be restored to completely unimpaired conditions, but they can be rehabilitated to support desirable biota and water quality (National Research Council 1996; Booth 2005;

Table 1. Common site-scale rehabilitation techniques applied in urban areas.

Bank stabilization
Erosion control focused on stream banks and shorelines
Rip-rap, geotextiles, retaining walls, sea walls
Planting riparian areas and shorelines with native woody plants or grasses
Removal of alien invasive riparian plants
Hydrological connectivity
Improved fish passage at dams
Daylighting of piped streams
Dam and culvert removal and retrofitting
Rip-rap, retaining wall, and seawall removal
Levee and dike breaching and setbacks
Meander and wetland creation
Off-channel habitat and floodplain reconnection
Decreasing the amount of impervious surfaces
Hydromorphological complexity
Placement of large wood, gabions, boulders, or gravel in stream channels
Placement of large wood and brush in lakes and estuaries
Aquatic macrophyte reestablishment in lakes and estuaries
Wastewater and storm water management
Wastewater (industrial, institutional, and domestic) collection and treatment
Storm water collection, separation, and treatment
Erosion control focused on uplands
Reducing the amount of impervious surfaces
Increasing evapotranspiration and infiltration of stormwater
Reestablishing wetlands and riparian vegetation
Installing green roofs, temporary ponds, bioswales, and rain gardens

Simenstad et al. 2005; Roni et al. 2008; Coles et al. 2012). The key is to understand at what scale problems are occurring and then apply a correct prescription that matches the scale of the problem.

Storm water must be controlled at its source (i.e., the catchment), which involves protections via land-use planning and regulation rather than attempts to rehabilitate degraded channels

Know Your Scale

Urbanization alters the biota via multiple pathways operating simultaneously at multiple scales (Figure 2). For example, the presence of a city on a river may result in a local physical or chemical barrier to fish migration that also alters fish populations far from those barriers (e.g., Cooke et al. 2004; Regier et al. 2013). Conversely, well-meaning mitigation projects are implemented at the site or reach scale in streams, lakes, and rivers, when many of the limiting factors are occurring at the watershed scale (e.g., Fausch et al. 2002; Roni et al. 2002; Scott et al. 2002; Strayer et al. 2003; Wang et al. 2003, 2011; Moerke and Lamberti 2006; Beechie et al. 2010; Regier et al. 2013). This is not to say that local projects are meaningless because they can have cumulative effects, especially when it comes to watershed rehabilitation or managing stormwater (Stanfield 2012).

Typically, however, rehabilitation is planned and implemented at the site (10s to 100s of meters) or segment (1,000s of meters to kilometers) scale. Stanfield (2012) suggested that assessing multiple sites along a segment can guide when and where local rehabilitation may be effective. However, it is almost always more effective to perform rehabilitation at watershed or basin scales, with a focus on recovering natural flow regimes (e.g., Frissell and Nawa 1992; Muhar 1996; Poff et al. 1997; Booth 2005; Wohl 2005; Bernhardt and Palmer 2007; Jansson et al. 2007). Therefore, the priority actions for urban rehabilitation are to (1) protect existing upstream high-quality catchments and habitats and (2) reestablish ecosystem processes and connectivity in the altered places (especially water quality and hydrological regime), before attempting to rehabilitate specific sites lower in the watershed (National Research Council 1992, 1996; Booth et al. 2004; Booth 2005; Roni et al. 2002, 2008; Bernhardt and Palmer 2007; Beechie et al. 2008). These are also precepts proposed by McHarg (1969) and Poff et al. (1997), which are similar to recommendations by Noss (2000) for maintaining ecological integrity at regional scales. Of course, resource managers must recognize that lag times for responses may range from 1 to 100 years or longer (Roni et al. 2002, 2008; Bernhardt and Palmer 2007; Beechie et al. 2008), and results may not be evident immediately. In the following five subsections we summarize the major rehabilitation techniques and their known limitations (Table 1).

First: Rehabilitate the Watershed

Watershed rehabilitation involves two distinct issues: management of natural land cover and managing stormwater entering via rapid runoff from impervious surfaces.

Natural Land Cover

In forested ecosystems, watersheds that have experienced timber harvest or conversion to agriculture have generally higher bedloads, embeddedness, sediment loads, and less stable flows (Sutherland et al. 2002). We note that this is the natural condition for streams in dryer ecosystems (Dodds et al. 2004), but most resource managers in temperate regions would likely view achieving a high percentage of native vegetative cover within a watershed as beneficial. However, achieving that goal is challenging from multiple perspectives.

First, watersheds vary in size and complexity and span multiple social, economic, and political boundaries with different human densities, cultural values, and land uses. This makes coordination difficult and regulatory approaches problematic. The solution is often achieved through independent watershed councils that promote stewardship and coordination (e.g., Huron River Watershed Council 2013), but rehabilitating natural land cover requires participation by not only public lands managers but in some cases thousands of private landowners.

A second issue is that it is very difficult to relate specific management actions to outcomes. Most watershed rehabilitation

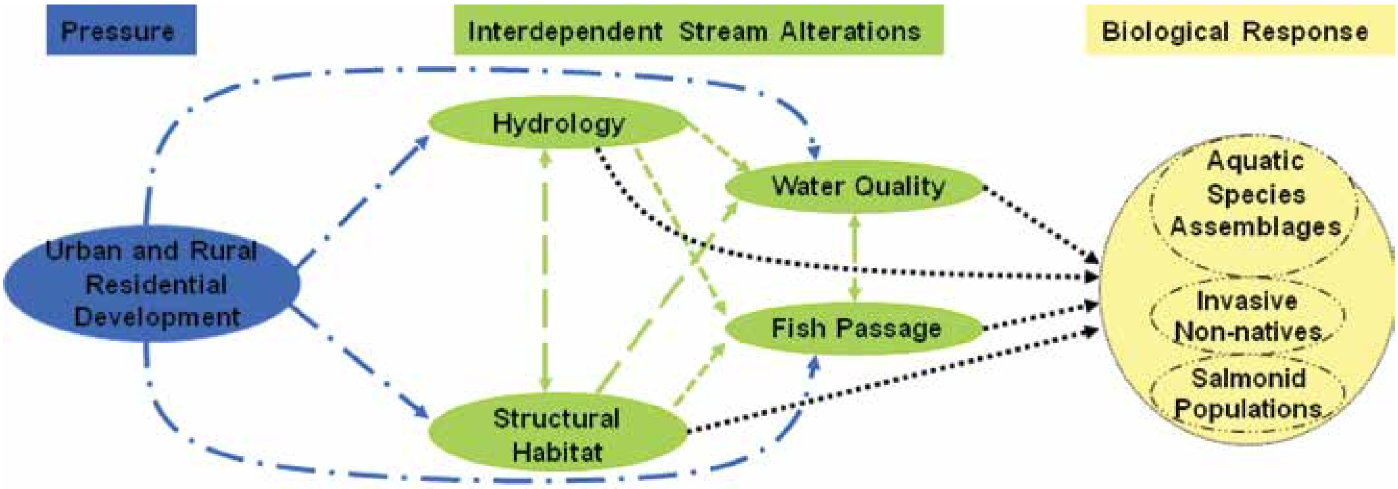

Figure 2. Interrelationships between urbanization pressures, interdependent stream alterations, and biological responses (IMST 2010).

efforts focus on encouraging riparian rehabilitation or best management practices that minimize agricultural runoff or erosion, the former because benefits are disproportionately large for the land area conserved (Quinn et al. 2001) and the latter because conversion of land to less-developed land covers is impractical (Allan 2004). However, the relationship between agricultural land cover and stream conditions is best described as highly variable with nonlinear relationships occurring at multiple scales. Some have reported that agricultural land use seems to have few effects on streams until about 30% to 50% of the watershed is farmed (e.g., Allan 2004), whereas Wang et al. (1997) reported high fish index of biotic integrity scores at sites with 80% agriculture. However, Trautman (1957) noted the demise of sensitive Ohio fishes in watersheds that experienced any loss of forest cover, and Gammon (2005) described how the Wabash River and its fish assemblages were altered soon after the land was cleared for farming. Apparently, other factors are at play, including what one uses as reference conditions and indicators.

So what are resource managers to do? It may be best to focus on riparian rehabilitation because that habitat has the most well-documented effects on stream condition (Naiman and Decamps 1997), and it also confers local habitat benefits at the reach scale (Brewer 2013). However, we note three caveats: (1) riparian rehabilitation can take many forms, depending on local physiographic conditions (a.k.a. one size fits none; Allan 2004); (2) in many watersheds extensive impervious surface coverage can override riparian services (Coles et al. 2012); and (3) extensive pipe networks can bypass riparian zones (Brewer 2013).

Storm Water

Storm water management is critical to small urban streams because runoff effects are especially severe. Some studies suggest that beyond 5%–15% urbanization diversity declines rapidly (Paul and Meyer 2001) because of the presence of impervious surfaces that result in rapid runoff (flashiness) that affects bank stability, hydrological connectivity, and hydromorphological complexity. To be effective, storm water must be controlled at its source (i.e., the catchment), which involves protections via land-use planning and regulation rather than attempts to rehabilitate degraded channels (Cairns 1989; Booth et al. 2004). Although a serious problem, there are a variety of prescriptions available.

The key to storm water management is to break the direct connection between the impervious surface and the stream (Cairns and Palmer 1995). There are a variety of available techniques: reconnecting stream channels to their floodplains, wetland and mini-natural area creation, reestablishing riparian vegetation, reducing the amount of impervious surfaces, and installation of green roofs, temporary ponds, bioswales, and rain gardens (Booth et al. 2004; Brand and Snodgrass 2010; IMST 2010; Schaeffer et al. 2012; City of Portland 2012a; Yeakley et al., 2014). These techniques function by increasing evapotranspiration and infiltration to the groundwater while reducing the volume of water routed directly into streams. Implementation of such green infrastructure also sequesters pollutants that might be flushed directly in high concentrations; however, Pataki et al. (2011) reported that bioswales may be nutrient sources depending on their management.

Storm water management has the added benefit of serving as aquatic habitat. Brand and Snodgrass (2010) determined that storm water retention ponds supported more amphibian breeding and rearing than natural wetlands, which were intermittently wet. Schaeffer et al. (2012) reported that a carefully designed and managed storm water retention pond provided habitat for 9 years for three regionally rare fish species that require clear water and dense aquatic macrophytes.

Second: Further Improve Wastewater Treatment

There is ample evidence that wastewater treatment benefits stream assemblages. In most developed nations, sewage and industrial effluent treatment have become commonplace, reducing waterborne diseases, improving water quality, providing opportunities for water-based recreation, and rehabilitating aquatic biological assemblages. Gammon (1976) and Hughes and Gammon (1987), respectively, reported only minor effects on fish assemblages exposed to treated urban wastewaters along 340 km of the Wabash River, Indiana, and 280 km of the Willamette River, Oregon—although both systems also endured agricultural pollution and channel modification. Weinbauer et al. (1980) found significantly improved water quality, fisheries, and aquatic biota in a 112-km reach of the Wisconsin River, Wisconsin, following treatment of paper and pulp mill effluents. Yoder et al. (2005) reported substantial improvement in Ohio fish assemblages following 20 years of increasingly improved urban sewage treatment. Mulvey et al. (2009) found that the major stressors on stream biotic assemblages in the Willamette Basin, Oregon, were excess temperature, riparian disturbance, and streambed instability, rather than urban sewage.

Although wastewater treatment is effective, we note that it is not universal and many rivers in developing nations suffer from severe pollution. Massoud et al. (2009) concluded that central wastewater treatment options in developing nations were inadequate because of infrastructure expense (especially collection costs); they suggested that decentralized strategies would be far more effective. However, Paulo Pompeu (Departmento de Biologia, Universidade Federal de Lavras, Lavras, Minas Gerais, Brazil, unpublished data) has found that secondary treatment of 70% of the sewage of the Belo Horizonte Metropolitan Region resulted in substantial recovery of the fish assemblage of the Rio das Velhas.

Even though most wastewater in developed nations is treated, two major problems remain. First, storm water flows (containing nutrients and toxins) can rapidly overwhelm treatment facilities, because in many cases storm water and wastewater systems are combined, and untreated water is released during storm events (Field and Struzenski 1972). Because flow separation is problematic and expensive, wet weather retrofits are often applied (Szabo et al. 2005). Second, treated wastewaters deliver untreated personal care products, pharmaceuticals, hormones, fire retardants, plasticizers, property maintenance chemicals, nanoparticles, heavy metals, solvents, and organochlorines (Dunham, 2014; Foster et al., 2014). Up to 200 of these largely unregulated and unmonitored emerging contaminants (many of which are endocrine disruptors) are released by wastewater treatment plants and in storm waters (Ritter et al. 2002). In addition, streams and lakes receiving treated wastewaters still experience increased nutrient loadings, especially where wastewaters comprise much of the flow. In any case, urban managers can become familiar with wastewater systems in their jurisdictions, implement techniques for removing untreated chemicals from the waste stream by regulation and treatment, and know how those systems are operated and their limitations.

Third: Rehabilitate Longitudinal, Lateral, and Vertical Hydrological Connectivity

Improvements in hydrological connectivity result in increased movement of water, sediment, wood, and biota longitudinally, horizontally, and vertically (Pess et al. 2005a). Dam and culvert removal—or retrofitting—improves longitudinal connectivity and fish passage and downstream movement of sediment and large wood (Pess et al. 2005b; Price et al. 2010). Most studies we reviewed have been in forested areas where fish showed rapid positive responses to such changes when those improvements were properly designed; that is, culverts were appropriate for all life stages and most flows (Beechie et al. 2008; Roni et al. 2008). However, urban dam removals and modifications also improve fish passage (Blough et al. 2004).

Improved horizontal connectivity rehabilitates floodplains through levee breaching or setbacks, rip-rap removal, meander creation, and off-channel habitat reconnection (Pess et al. 2005a). Most studies we examined have involved rural and forested streams, and the majority indicated improved physical or biological conditions (Beechie et al. 2008; Roni et al. 2008)—and some studies have found positive effects in urban environments. Levell and Chang (2008) reported physical improvements 2 years after channel restructuring relative to an urban site but found less channel and substrate stability than in a nonurban reference site. Kaushal et al. (2008) reported that a rehabilitated reach of a Baltimore, Maryland, stream had significantly lower nitrate concentrations than an unrehabilitated reach of the same stream. Daylighting (reexposing piped streams to allow flooding and riparian vegetation) has occurred in several U.S. streams, but too few have been monitored to arrive at conclusions concerning ecological effects (Bucholz and Younos 2007). The greatest challenge is that urban infrastructure may constrain such measures (Brown et al. 2009; IMST 2010), but we believe that opportunities exist in many cities that have abandoned or neglected waterfronts and riparian zones. Those areas might be rehabilitated as public green spaces within the historic floodplain (City of Portland 2012b; Yeakley et al., in press).

Vertical connectivity is the exchange between groundwater and surface water in aquatic systems, but techniques for rehabilitating vertical connectivity rarely have been evaluated (Boulton 2007). Kaushal et al. (2008) reported that groundwater in a rehabilitated Baltimore, Maryland, stream reach had significantly lower nitrate concentrations and higher denitrification rates than in an unrehabilitated reach of the same stream. Denitrification was significantly higher in reaches where rehabilitation promoted overland flooding and seepage to groundwater versus seepage in rehabilitated reaches that were unconnected to their floodplains. Groffman et al. (2003) also found that denitrification potential decreased with channel incision and lowered water tables in urban riparian zones. In addition, increased vertical and horizontal connectivity with the water body, as opposed to stream incision or lake drawdown, is necessary for rehabilitating and sustaining riparian woody vegetation versus upland vegetation (Scott et al. 1999; Groffman et al. 2003; Kaufmann et al., in press). We note that among the major rehabilitation techniques, improved hydrological connectivity frequently shows the most immediate responses in fish passage and water quality improvement.

Fourth: Improve Hydromorphological Complexity

Common hydromorphological rehabilitation techniques include placement of large wood, boulders, or gravel into stream channels. In forest streams, those alterations usually increased physical habitat complexity, but their biological effects are uncertain because of insufficient monitoring, method and stream variability, and study design flaws that make increased fish production indistinct from increased fish concentration (e.g., Roni et al. 2005, 2006, 2008; Thompson 2006; Stewart et al. 2009; Whiteway et al. 2010). In addition, urban streams experience more flashiness and poorer water quality than forest streams, which together may override hydromorphological complexity (Larson et al. 2001; Booth 2005; Brewer 2013). Most studies reviewed suggest that local rehabilitation actions have little effect. Larson et al. (2001) reported that adding large wood did not improve benthic macroinvertebrate assemblages in Washington urban streams. Gravel augmentation in a highly disturbed California river increased Chinook Salmon (*Oncorhynchus tshawytscha*) spawning activity (Merz and Setka 2004) and egg-to-alevin survival (Merz et al. 2004) but not macroinvertebrate densities (Merz and Ochikubo Chan 2005). Violin et al. (2011) found no differences between macroinvertebrate assemblages and instream physical habitat of rehabilitated versus degraded urban streams in the North Carolina Piedmont. In summary, restoration of local structural complexity is unlikely to provide benefits and unlikely to persist if flow modifications and hydrological connectivity are not also addressed (Frissell and Nawa 1992; DeGasperi et al. 2009). The rare exceptions may be cases where a stream is so degraded that all within-channel habitat is lacking, but we note that those streams are likely experiencing large-scale problems as well.

Fifth: Last and Least, Stabilize Banks

Several types of erosion control techniques (rip-rap, geotextiles, gabions, retaining walls, sea walls) are employed more to protect economically valuable infrastructure than to rehabilitate natural processes of channel and shoreline erosion and migration. Such techniques transmit the energy of moving water downstream or down current to other shorelines and river banks. Because these bank hardening techniques are directed toward infrastructure protection and typically impair biotic condition and ecological processes (Sedell and Beschta 1991), we do not emphasize them in this review.

Riparian vegetation stabilizes banks and improves conditions for sensitive fish taxa in lakes, streams, and rivers. Vegetation plantings can decrease bank erosion and increase shredder macroinvertebrate diversity (Sudduth and Meyer 2006) while decreasing solar inputs, but the magnitudes of these effects on urban fish assemblages are uncertain. In lakes, Kaufmann et al. (in press) reported that increased littoral and riparian vegetation cover complexity was associated with increased richness of eutrophication-intolerant fish species (Figure 3A) and decreased richness of eutrophication-tolerant fish species (Figure 3B). Groffman et al. (2003) and Roni et al. (2008) emphasized that riparian vegetation is more likely to persist if flow modifications and hydrological connectivity are also addressed; however, additional studies are needed to document those assumptions. In contrast, rip-rap has an opposite effect; however, more controlled and multisite studies are needed. Schmetterling et al. (2001) reported that rip-rap reduced the development of undercut banks, gravel deposits, and riparian vegetation, which provide fish cover, and Kondolf et al. (2006) indicated that rip-rap increased downstream erosion in rivers.

In summary, urban water bodies cannot be restored to predisturbance conditions, but they can be improved to support desirable biota and water quality. Rehabilitation of urban aquatic ecosystems is challenging because of multiple and interacting biophysical urban constraints, as well as continuous inputs from and interactions with urban residents. Multiple rehabilitation measures taken at the catchment scale are most effective if they focus on reestablishing ecosystem processes and rehabilitating natural vegetation, hydrological regimes, and water quality—before attempting to rehabilitate degraded instream hydromorphology at the site scale. Resource managers skilled at diagnosing the scale at which problems are occurring will be able to apply the best prescription. And in urban sites, fisheries professionals working closely with urban planners and wastewater engineers will be able to ameliorate effects of storm water.

Our review focused on rehabilitation of urban streams that had been damaged previously. Urbanization is an ongoing phenomenon, with a progressively larger proportion of humans moving into urban areas that are likely to expand. Thus, more streams are likely to become urbanized in the future. Ideally, there would be a way to prevent damage inexpensively rather than repair extensive damage expensively. We will explore that topic in Hughes et al. (2014) and point to what still needs to be learned about urban streams to make mitigation more effective, including climate change and sociological issues.

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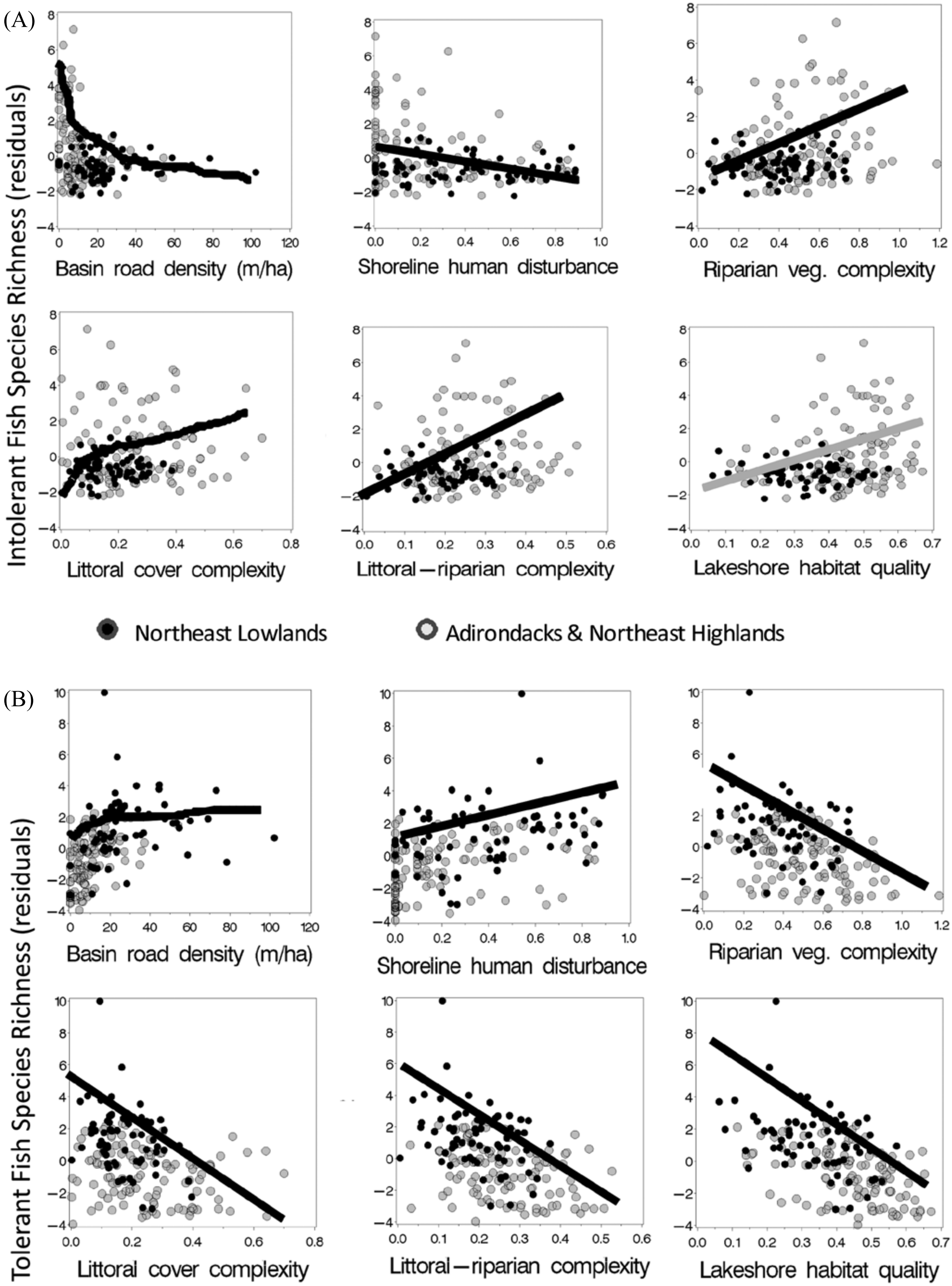

Figure 3. Responses of intolerant fish (A) and tolerant fish (B) to lake littoral and riparian condition (adapted from Kaufmann et al., in press). Richness regression residuals were used to calibrate for the effect of lake area on species richness. Lines are 95th percentile quantile regressions.

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