Landscape and Urban Planning 143 (2015) 219–229

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Research Paper

Watershed features and stream water quality: Gaining insight through path analysis in a Midwest urban landscape, U.S.A.

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HIGHLIGHTS

- Stream water conductivity, total nitrogen and phosphorus concentration were studied.
- Path analyses integrated social and biophysical variables' effect on water quality.
- Road density, percent crop land, and education level had greatest total effects.
- Quantifying relationships among variables can inform actions to protect urban streams.

ARTICLE INFO

Article history:
Received 6 August 2014
Received in revised form 29 July 2015
Accepted 2 August 2015
Available online 26 August 2015

Keywords:
Coupled human and natural systems
Path analysis
Urban hydrology
Urban streams
Stream water conductivity
Stream water nutrients

ABSTRACT

Urban stream condition is often degraded by human activities in the surrounding watershed. Given the complexity of urban areas, relationships among variables that cause stream degradation can be difficult to isolate. We examined factors affecting stream condition by evaluating social, terrestrial, stream hydrology and water quality variables from 20 urban stream watersheds in central Iowa, U.S.A. We used path analysis to examine and quantify social and ecological factors related to variation in stream conditions. Path models supported hypotheses that stream water quality was influenced by variables in each category. Specifically, one path model indicated that increased stream water conductivity was linked to high road density, which itself was associated with high human population density. A second path model revealed nitrogen concentration in stream water was positively related to watershed area covered by cropland, and that cropland increased as human population density declined. A third path model indicated phosphorus concentration in stream water declined as percent of watershed residents with college education increased, although the mechanism underlying this relationship was unclear and could have been an artifact of lower soil-derived nutrient input from watersheds dominated by paved surfaces. To improve environmental conditions in urban streams, land use planning strategies should include limiting or reducing road density near streams, installing treatment trains for surface water runoff associated with roads, and establishing vegetated buffer zones to reduce inputs of road salt and other pollutants. Additionally, education/outreach should be conducted with residents to increase understanding of how their own behaviors influence stream water quality.

1. Introduction

In 2011, more than half of the world's population (52.1%) resided in urban areas. In the United States (U.S.A.), the proportion of urban dwellers was much greater at 82.4% (United Nations, 2011). The growth of the urban population in the U.S.A. is increasing at a faster rate (12.1% between 2000 and 2010) than the global population growth rate (9.7% during the same period; U.S. Census Bureau, 2012). Further, the rate of expansion of urban land cover is disproportionately greater than human population growth alone. For

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http://dx.doi.org/10.1016/j.landurbplan.2015.08.001

example, in four Iowa (U.S.A.) cities, population growth rates from 3% to 11% between 1990 and 2000 drove urban land cover expansions of 26% to 80% (Bowman, Thompson, Tyndall, & Anderson, 2012; see also Liu, 2005; Seto, Guneralp, & Hutyra, 2012). Changes associated with expansion of urban land cover types (e.g., hard surfaces associated with roads and buildings) are profound, cumulative, and rarely, if ever, reversed (McGranahan & Satterwaite, 2003; Seto, Fragkias, Guneralp, & Reilly, 2011; Wu & Thompson, 2013). Thus, understanding the relationships among humans, their activities, and natural systems in urban landscapes is increasingly important.

1.1. Urban landscapes and watersheds

Urban landscapes are complex systems with many potential linkages between human and natural elements (Grimm et al., 2008; Liu et al., 2007). Addition of infrastructure, such as roads, buildings, and storm sewers often causes damage to natural landscapes that is difficult to repair or mitigate. For example, declines in the size and quality of natural areas embedded in urban and peri-urban landscapes have strong negative effects on biodiversity (e.g., McKinney, 2002, 2008). Human activities within urban systems, such as pet ownership (and pet waste management), motor vehicle use, and application of lawn fertilizer, also can lead to high concentrations of pollutants (Fissore et al., 2011).

Conditions in urban streams reflect changes in the upland landscape, including changes in hydrology and water quality (Arnold & Gibbons, 1996; Carvalho et al., 2010; DiDonato et al., 2009; Hatt, Fletcher, Walsh, & Taylor, 2004; Nagy, Lockaby, Kalin, & Anderson, 2012; Olivera & DeFee, 2007; Sun, Chen, Chen, & Ji, 2013; Walsh et al., 2005; Wu, Thompson, Kolka, Franz, & Stewart, 2013). For example, increases in total discharge, peak discharge, and flashiness have been reported in urban streams as impervious land cover increases within a watershed (Nelson et al., 2009; Schoonover, Lockaby, & Helms, 2006; Wu et al., 2013). Elevated concentrations of nutrients, metals and sediments have also been reported in urban streams (Deemer et al., 2012; Grayson, Finlayson, Gippel, & Hart, 1996; Hatt et al., 2004). Phosphorus and nitrogen from fertilizer applied to lawns, sediment and salts from roads, and increased runoff from roofs delivered to streams rapidly via storm sewers have been identified as potential contributors to stream degradation in urban areas (Adachi & Tainosho, 2005; Fissore et al., 2011; Negishi, Negochi, Sidle, Ziegler, & Nik, 2007; Ragab, Bromley, Rosier, Cooper, & Gash, 2003). Given changes in urban stream hydrology and habitat and water quality, biological communities are also likely to be affected in urban streams (Walsh et al., 2005).

1.2. Use of path analysis to integrate social and environmental variables affecting urban streams

Complex social and ecological interactions in urban systems make it difficult to identify mechanisms that drive variation in urban stream characteristics (Cadenasso, Pickett, & Schwartz, 2007). Path analysis, an extension of multiple linear regression, is a helpful tool for gaining insight into strengths and mechanisms of cause–effect relationships within interaction webs (Bollen, 1989; Cohen, Cohen, West, & Aiken, 2003; Grace, 2006). Path analysis operates by simultaneously evaluating multiple hypotheses of causal relationships, and generating quantitative estimates of direct, indirect, and total effects of independent variables on dependent variables. This technique has been applied, for example, to examine relationships among land cover, storm characteristics, stream hydrology, and water quality variables in Phoenix, Arizona, U.S.A. (Lewis & Grimm, 2007). In that study, path models indicated that abundance of impervious surface was an especially important contributor to nitrogen export from streams located within the watershed. Thus, this approach has promise for furthering our understanding of complex relationships in urban systems, and we propose that it could be especially useful for more strongly integrated assessments of social and environmental system variables as factors that directly and indirectly influence urban stream water quality.

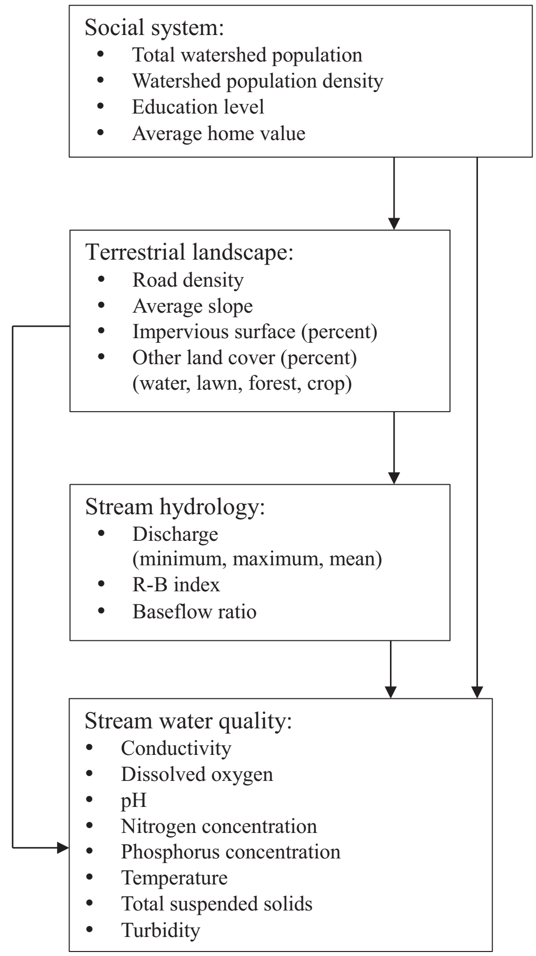

Fig. 1. Hypotheses of direct and indirect relationships among four categories of variables: social system, terrestrial landscape, stream hydrology, and stream water quality. Arrows represent hypothesized relationships among variables measured in this study.

1.3. Research objective and hypotheses

Our research objective was to gain insight into relationships among social system, terrestrial landscape, stream hydrology, and stream water quality attributes within urban headwater basins. We measured multiple variables within each of these four attribute categories for 20 urban watersheds in five central Iowa (U.S.A.) cities. We used path analysis to explore hypotheses of relationships within each watershed (Wright, 1934). Path analysis was conducted based on an overall conceptual model of mechanisms by which humans were predicted to directly and indirectly influence the terrestrial landscape, instream hydrology, and water quality (Fig. 1). The structure of our overall conceptual model was based on results from previous investigations of relationships among social systems, terrestrial landscape characteristics, and stream characteristics (e.g., Arnold & Gibbons, 1996; Quinn, 2013; Rose & Peters, 2001; Walsh et al., 2005; Wenger et al., 2009).

Specifically, we expected to find evidence from our investigation that humans (social system) both directly and indirectly influence