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A geospatial analysis of land use and stormwater management on fecal coliform contamination in North Carolina streams

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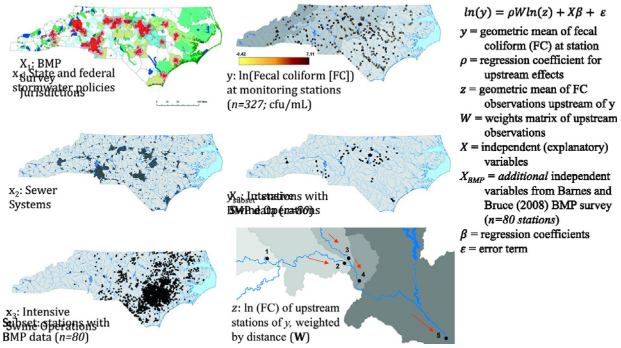
HIGHLIGHTS

- Non-point source pathogen pollution is a leading cause of stream impairment in the US.
- We use spatial regressions of fecal coliform (FC) in North Carolina with urban variables.
- Model can help target stream restoration investments and water quality mitigation.
- Policy/urban -variables project FC levels at unmonitored stream network locations.
- Endogeneity affects relationships between FC levels and state water protection policies.

GRAPHICAL ABSTRACT



$$\ln(y) = \rho W \ln(z) + X\beta + \varepsilon$$

y = geometric mean of fecal coliform (FC) at station
ρ = regression coefficient for upstream effects
z = geometric mean of FC observations upstream of y
W = weights matrix of upstream observations
X = independent (explanatory) variables
X_{BMP} = *additional* independent variables from Barnes and Bruce (2008) BMP survey (*n=80 stations*)
β = regression coefficients
ε = error term

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ABSTRACT

Although non-point source (NPS) pathogen pollution is a leading cause of stream impairment in the United States, the sources of NPS pollution are often difficult to ascertain. While previous studies have employed land use regression methods to develop a greater understanding of the sources and dynamics of microbial NPS pollution, little work has explicitly considered the effects of local, state, and federal stormwater management policies on water quality across multiple watersheds or at larger spatial scales. How do land use and stormwater management efforts collectively influence fecal coliform (FC) levels at a regional or multiple-watershed scale? We construct a unique spatial regression model of stream FC pollution ($n = 327$ monitoring stations) throughout the state of North Carolina (USA), incorporating both land cover and urban development variables. We then use a subset of our data ($n_{bmp} = 80$ monitoring stations) to incorporate local stormwater control measures and stormwater management policies. Results demonstrate that the inclusion of policy and management variables improves the explanatory capacity for FC levels ($R^2 = 0.4412$ versus $R^2 = 0.5323$). Locally, this model can be used to better target stream restoration and water quality mitigation actions and investments, as well as help to predict FC levels at unmonitored locations throughout North Carolina's stream network. More generally, the novel structure of this model can also help examine the large-scale effects of stormwater regulations on surface water pathogen levels, helping researchers and planners better predict water quality in the absence of extensive monitoring station data.

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1. Introduction

Early U.S. water pollution control efforts focused on point sources of surface water pollution, and included federal permitting efforts such as the National Pollution Discharge Elimination System (NPDES) created as part of the U.S. Clean Water Act (CWA; 33 U.S.C. § 1251 *et seq.*). More recently, attention has centered on the effect of nonpoint source (NPS) pollution, which is now a leading cause of impaired surface waters in the Unites States (Rissman and Carpenter, 2015). NPS pollutants are composed of contaminants originating in diffuse stormwater runoff or other sources (e.g. septic systems, sewer leakage) that enter water bodies from many unknown locations, thus making their identification and mitigation challenging.

Of particular concern is contamination by pathogens, which are measured through metrics of fecal indicator bacteria. Such bacteria are present in the feces or other wastes of humans and other warm-blooded animals. Sources of surface water fecal contamination include wastewater treatment plants, on-site septic systems, domestic and wild animal feces, and municipal sewer overflows after heavy storm events (USEPA, 2012). Nationwide, pathogens are now the leading cause of impairment of rivers, streams, and estuaries (USEPA, 2015). In North Carolina (USA), fecal coliforms (FC) are the third largest cause of impairment for rivers and streams, with only “biota of unknown sources” (i.e. undetermined biological sources) and mercury cited as larger sources of contamination (USEPA, 2014).

A growing body of research has aimed at predicting water quality degradation from land cover variables, including development levels, urbanization patterns, and impervious surface coverage (e.g. Mallin et al., 2009). Most previous studies of NPS pollution have generally been focused on low-order streams in small catchments with varied land uses that are sampled over time periods of less than one year (Baker, 2005). However, similar studies have not been conducted at a multi-watershed, state-level scale. Furthermore, previous studies have not incorporated stormwater management policies into a predictive model of surface water quality to determine how such programs impact contaminant levels.

In this study, we investigate the relationship between land cover and FC contamination at a range of geographic scales. We base our work in the State of North Carolina (USA), which has both a long history of water quality impairments (Buzzelli et al., 2004; Smith, 2012; Humphrey et al., 2013; Humphrey et al., 2015) and a range of local and state-level policies aimed at improving stormwater quality and modifying development patterns (Smith, 2012; Berke et al., 2013). North Carolina has experienced rapid population growth within the past two decades, increasing from ~6.6 million in 1990 to ~9.6 million in 2010 (NCOSBM, 2016). Increased development, extension of road networks and impervious surface coverage, and increased urban density makes North Carolina an ideal place to explore the impacts of land cover, land use, and stormwater management practices on FC concentrations throughout a stream network at the regional- and state-scales. In this article, we draw on extensive surface water monitoring data within the State in order to implement a geo-spatial regression analysis exploring the relationship between FC contamination levels and a variety of explanatory variables, including land cover and land use, impervious cover, road network designs and density, and population and housing patterns. Given the state's projected future growth (NCOSBM, 2016), this study may be particularly useful for future policy development aimed at improving water quality.

This study is unusual in that we explicitly focus on hierarchical scales of policy focus, including the presence of local stormwater management practices and policies as model covariates to determine whether such actions are associated with lower FC levels in surface water. Based on these models, we ask, how are local stormwater practices and policies associated with FC levels in river networks? This type of analysis, which controls for hydrologically relevant environmental, population, and state and federal policy factors, represents a potentially useful tool for land-use planners, resource managers, and regulatory agencies for determining the current conditions of water quality in *unmonitored* river networks. Using locally-calibrated models as predictors, planners—in both the domestic and international context—can gather information to help prioritize future mitigation and restoration efforts, as well as analyze the effectiveness of local government stormwater practices and policies.

1.1. Determinants of fecal coliform concentrations

Exposure to pathogenic bacteria from recreational contact with natural water can result in problematic health effects, including skin rashes, eye and nose infections and acute gastrointestinal illness, including cramps and diarrhea (Soller et al., 2015; see Appendix A for more information). Many studies have investigated the link between land cover and water quality (see Brabec et al., 2002; McMichael et al., 2013). Numerous additional studies have found complex relationships between water quality and factors such as population density (Peierls et al., 1991; Frenzel and Couvillion, 2002; Baker, 2005), housing density (Young and Thackston, 1999; Goonetilleke et al., 2005; Lohse and Merenlender, 2009), and commercial, industrial, and residential zoning (Selvakumar and Borst, 2006; Mallin et al., 2009; Harclerode et al., 2013). Studies have also revealed negative relationships between FC and septic tank density (Kelsey et al., 2004; Cahoon et al., 2006) and impervious surface levels. Arnold and Gibbons (1996) found that higher impervious surface cover is associated with lower water quality, suggesting community planning, site-level planning and design, and land use regulation strategies for reducing impervious surfaces.

Specific to FC contamination, strong relationships have been found between fecal bacteria concentrations and environmental variables, such as rainfall, temperature, salinity, and turbidity (e.g. Mallin et al., 2000; Gentry et al., 2006; Hathaway et al., 2010; Liao et al., 2014). Additionally, studies have found that FC levels can be tied to housing and population density (Mallin et al., 2000; Frenzel and Couvillion, 2002; Walters et al., 2011), impervious area and urban land uses (Sliva and Williams, 2001; Mallin et al., 2009; Walters et al., 2011; Chow et al., 2013; Strauch et al., 2014), and domestic animal density (Young and Thackston, 1999; Walters et al., 2011). Other studies have revealed correlations that FC levels appear to be higher in basins that have an established sewer network compared to those in which such a network is absent (e.g. Young and Thackston, 1999). However, studies building on these findings need to control for both population and septic field density (Sowah et al., 2014; Spirandelli, 2015). Land covers also impact water quality in a variety of ways. Typically, forested land cover is negatively correlated with FC bacteria levels, as forests reduce runoff and promote water infiltration into the surrounding soil, thus improving stream water quality (Tong and Chen, 2002). However, forested land cover may be positively correlated with FC bacteria levels in streams and other waterways if the area provides suitable and frequently utilized habitat for animals, particularly mammals, as this may lead to an increase in the total amount of animal feces, and thus coliform bacteria, present in nearby monitored waters (Fisher et al., 2000; Smith et al., 2001).

Federal, state and local governments have devised a variety of programs to control surface water runoff. Perhaps the most important aspect of these programs involves post-construction stormwater management in new development and redevelopment. These provisions mandate that communities adopt ordinances that may require the use of structural best management practices (BMPs) for stormwater control. However, there are many complexities plaguing implementation, monitoring, maintenance and enforcement of structural stormwater management programs, partly because the success and long-term viability of BMPs is quite sensitive to the accuracy of initial designs and the extent of dedicated maintenance efforts (Ellis and Marsalek, 1996). See Appendix B for more information on stormwater control programs and policy, generally.

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