

Effets des rénovations d'infrastructures vertes à l'échelle du bassin versant sur la qualité des eaux pluviales urbaines : une étude de bassin versant jumelée pour quantifier l'élimination des nutriments et des sédiments

Effects of watershed-scale green infrastructure retrofits on urban stormwater quality: A paired watershed study to quantify nutrient and sediment removal

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RÉSUMÉ

L'infrastructure verte (IG) est une méthode de plus en plus utilisée pour traiter les polluants des eaux pluviales, mais il existe peu de preuves concernant son rendement à l'échelle du bassin versant. Blueprint Columbus est un effort de la ville de Columbus, Ohio, États-Unis, pour moderniser la biorétention et la chaussée perméable dans les zones développées existantes. Les changements dans la qualité de l'eau résultant des effets combinés de nombreuses pratiques d'IG installées dans des bassins versants de traitement de 11,5 et 47,8 ha ont été quantifiés à l'aide d'une approche de bassin versant jumelé sur une période de 3,5 ans. Les concentrations d'azote total (TN), de phosphore (TP) et de solides totaux en suspension (TSS) ont diminué de 13,7-24,1%, de 20,9-47,4% et de 61,6-67,7%, respectivement. L'atténuation du ruissellement par IG a contribué à des réductions significatives de la charge polluante de 24,0-25,4 % (TN), de 27,8-32,6 % (TP) et de 59,5-78,3 % (TSS). Les concentrations et les charges d'orthophosphate ont considérablement diminué. Les réductions de la concentration de SCT étaient semblables (dans une marge de 5 %) au pourcentage de l'étanchéité du bassin versant traité par IG. Les résultats démontrent que l'IG était efficace pour réduire les concentrations et les charges moyennes des événements de ruissellement à l'échelle du bassin versant.

ABSTRACT

Green infrastructure (GI) is an increasingly utilized method to treat stormwater pollutants, but little evidence exists regarding its performance at the watershed-scale. Blueprint Columbus is an effort by the City of Columbus, Ohio, USA, to retrofit bioretention and permeable pavement into existing developed areas. Changes in water quality resulting from the combined effects of many GI practices installed in 11.5 and 47.8 ha treatment watersheds were quantified using a paired-watershed approach over a 3.5-year period. Total nitrogen (TN), phosphorus (TP), and total suspended solids (TSS) concentrations decreased by 13.7–24.1%, 20.9–47.4%, and 61.6–67.7%, respectively. Runoff attenuation by GI contributed to significant pollutant load reductions of 24.0–25.4% (TN), 27.8–32.6% (TP), and 59.5–78.3% (TSS). Orthophosphate concentrations and loads significantly decreased. Reductions in TSS concentration were similar (within a margin of 5%) to the percent of the watershed imperviousness treated by GI. Results demonstrate that GI was effective in reducing runoff event mean concentrations and loads at the watershed-scale.

KEYWORDS

bioretention, low impact development, permeable pavement, water sensitive urban design, water quality

1 INTRODUCTION

The City of Columbus, Ohio, USA recently faced two different consent decrees from the Ohio Environmental Protection Agency: one for combined sewer overflows (CSOs) and one for sanitary sewer overflow (SSOs). SSOs result from infiltration and inflow of stormwater into sanitary sewer systems and degrade water quality in urban areas. With goals of reducing SSOs and total suspended solids (TSS) by 20%, the City of Columbus, Ohio, has retrofitted hundreds of GI practices into a single neighborhood.

Chinese sponge cities, Australia's Little Stringybark Creek, and select studies in cities in the USA are the only studies we have found that attempt to quantify the water quality changes resulting from GI implementation at watershed-scales (Yin et al., 2022; Walsh et al., 2021). Among these limited studies, even fewer use nearby control watersheds to account for annual and seasonal variability. To summarize those, nearly two decades of water quality monitoring in six catchments retrofitted with SCMs throughout Australia's Little Stringybark Creek revealed significant reductions in N and P, but not TSS to receiving streams (Walsh et al., 2021). Concentrations of TN, TP, and TSS were reduced by 58%, 38%, and 82%, respectively, in runoff from a 0.53 ha, residential catchment with sandy underlying soils in North Carolina, USA following the installation of an in-street bioretention cell, four permeable pavement parking stalls, and a tree filter treating 91% of the catchment (Page et al., 2015).

The research objectives of this study are to 1) to quantify changes in nutrients and sediment resulting from the implementation of GI at the watershed-scale, 2) discuss fundamental processes responsible for these water quality changes, and 3) provide recommendations on the efficacy of GI retrofits and to improve the outcomes and monitoring of projects at this scale.

2 METHODS

Two treatment watersheds, Cooke-Glenmont (11.5-ha) and Indian Springs (47.8-ha), and a control watershed, Beechwold (111.5-ha), in the Clintonville neighborhood of Columbus, Ohio, USA, were monitored for stormwater hydrology and water quality at their respective storm sewer outfalls using autosamplers. The control and treatment watersheds were located within a 1 km radius. Cooke-Glenmont had three bioretention cells installed that treated 66.5% of the watershed impervious area. All bioretention cells included 60 cm of loamy sand media (2-5% organic matter by mass) underlain by 30 cm of aggregate surrounding an underdrain (i. e., no internal water storage zone) and had 30 cm of bowl storage. Among the 32 bioretention cells retrofitted into Indian Springs, 11 extended into the street to intercept runoff along the curb. The remaining 21 cells were located behind the curb in front of houses. Bioretention cells were planted with (1) grasses and sedges, such as *Panicum virgatum* and *Carex morrowii*, (2) perennials, especially *Polygonatum odoratum* and *Rudbeckia fulgida*, and (3) shrubs such as *Hypericum frondosum*. Four roads/alleys were retrofitted with curb-to-curb permeable interlocking concrete pavement. All together, 69.7% of the watershed impervious area was treated by GI at Indian Springs.

This study utilized a "before-after, control-impact" paired watershed design to determine if water quality changes were due to the implementation of GI or other external factors, such as changes in climate or pollutant generation in the watersheds. "Before-after" refers to the time periods before and after GI was installed; "control-impact" refers to the control and GI-treatment watersheds. Smaller storm events of <5.1 mm were not sampled since they yielded insufficient runoff for laboratory analysis; furthermore, instances of equipment malfunction precluded sampling; otherwise, all storm events were sampled. At Beechwold, Cooke-Glenmont, and Indian Springs, 102, 67, and 40 storm events, respectively, were sampled for water quality during the project phases (Table 2). Storm events sampled for water quality represented 39.1–67.5% of the total observed rainfall.

Summary statistics for pollutant concentrations were determined using laboratory-reported event mean concentrations (EMC). Those derived from the data set included the number of observed events, median pollutant concentrations, and pollutant loads during each phase (i.e., pre-GI, or post-GI) for control and treatment watersheds. Pollutant loads from each watershed were determined as the product of pollutant EMC and runoff volume on a storm-by-storm basis. Analysis of covariance (ANCOVA) was used to compare treatment to control data. All data analysis was completed using R statistical software version 3.4.2 (R Core Team, 2020). A criterion of 95% confidence ($\alpha = 0.05$) was used.

3 RESULTS AND DISCUSSION

TN concentrations and loads were significantly ($p < 0.005$) reduced by 13.7% and 24.0%, respectively,

between the pre- and post-GI phases at Cooke-Glenmont. Reductions in TN concentrations and storm event loads between the pre- and post-GI phases at Indian Springs were 24.1% and 25.4%, respectively (Figure 1). Stormwater runoff attenuation provided by bioretention and capture of organic N within GI are responsible for this observed TN removal. TP concentrations were significantly higher at Cooke-Glenmont than Beechwold ($p < 0.005$) during the pre-retrofit period, likely due to the substantial forested cover in the watershed. TP concentrations and storm event loads significantly decreased ($p < 0.05$) by 20.9% and 32.6% at Cooke-Glenmont and by 47.4% and 27.8% at Indian Springs, respectively, with the adoption of GI.

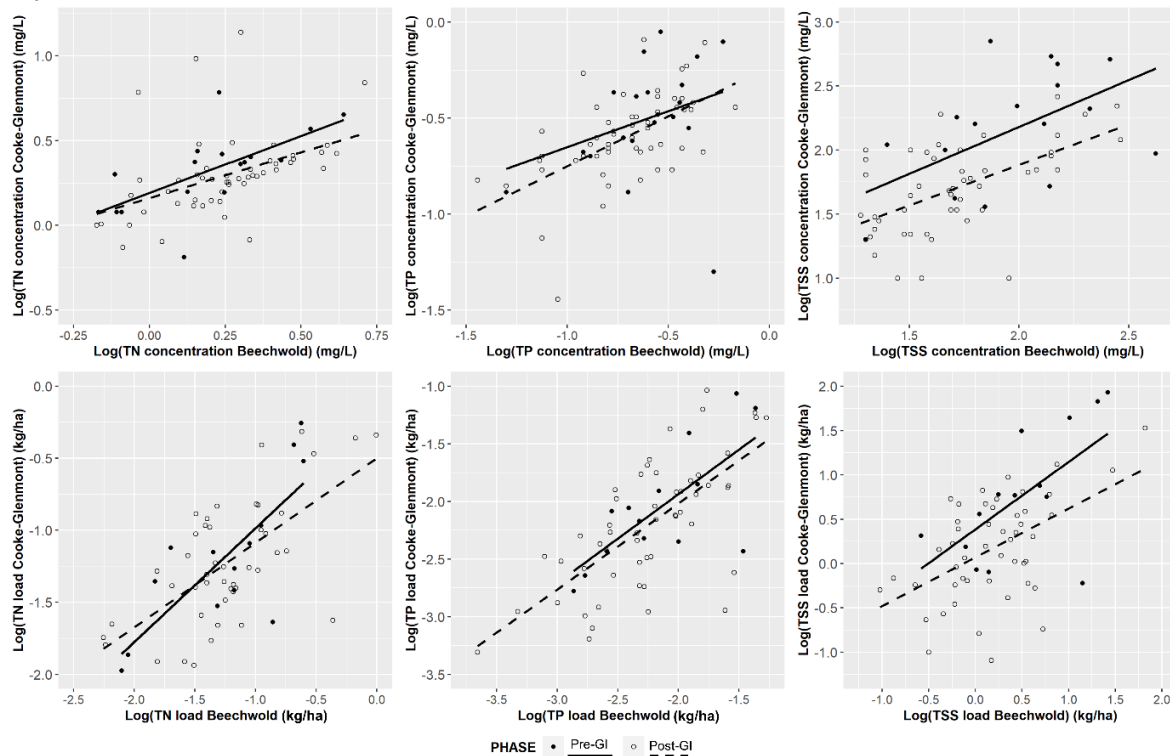


Figure 1 : ANCOVA models for total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS) concentrations and storm event loads at Cooke-Glenmont (CG). All differences significant unless data did not fit a linear model (Pre-GI TP concentrations)

Orthophosphate (OP) concentrations significantly decreased by 25.2% at Indian Springs with the installation of GI ($p < 0.001$). This OP reduction may be caused by sorption to silt, clay, and organic matter and vegetative uptake within the bioretention practices. Since the same bioretention media was utilized in Cooke-Glenmont and Indian Springs and phosphorus-containing fertilizers are prohibited in Ohio, the OP increases at the former and significant decreases at the latter may be related to types of GI implemented and bioretention hydrology. Even though the IWS design feature was not used in the permeable pavement at Indian Springs, past studies suggest the limestone aggregate and native clay subsoils perhaps allowed for the attachment of OP to iron and aluminum oxides on clay particles. Drake et al. (2014) found that OP concentrations were reduced in a permeable pavement practice by 26–35%. Braswell et al. (2018) also observed effective treatment of OP in permeable pavement, with significant reductions in concentration of 71%.

TSS concentrations and loads decreased by 61.6% and 78.3%, respectively, at Cooke-Glenmont with the installation of GI ($p < 0.001$) which treated 66.5% of the imperviousness area in the watershed. TSS concentrations decreased 67.7% between the pre- and post-GI phases at Indian Springs, where 69.7% of the impervious area in the watershed was treated by GI. At both Cooke-Glenmont and Indian Springs, reductions in TSS concentrations closely paralleled the watershed imperviousness treated by GI. Median TSS concentrations during the post-GI phase at both treatment sites (49 and 20 mg/L for Cooke-Glenmont and Indian Springs, respectively) were larger than those reported by the International Stormwater Best Management Practices Database for effluent from single bioretention cells and permeable pavements (10.0 and 26.0, respectively; Clary and Jones, 2017). This implies further TSS reduction is possible through greater GI implementation targeting treatment of a greater percentage of the watersheds.

4 SUMMARY AND CONCLUSIONS

GI treated particulates across a range of rainfall depths and intensities, and the majority of the pollutograph was well-treated, including nitrogenous compounds, phosphorus compounds, and sediments. Watershed-scale GI provided an aerobic environment for nitrification and biological conversion, and opportunities for plant uptake. Enhancements to GI that lengthen the contact time between soil media and stormwater and promote anaerobic conditions could have improved the ability of GI to abate nitrogenous pollutants. Watershed-scale GI also enhanced the removal of phosphorous species. OP concentrations and storm event loads increased in the treatment watershed with just bioretention but decreased in the treatment watershed with bioretention and permeable pavement, potentially meaning OP sorbed to permeable pavement aggregates and aluminum and iron oxides in the native clay soil. Interestingly, the percent TSS concentration reduction closely mimicked (within a margin of 5%) the percentage of watershed imperviousness treated by GI. This information is vital to estimate how watershed-scale GI performs for TSS removal. Further studies are needed to determine the optimum density, placement, and type of GI; to enhance GI media, hydraulic design, and planting to encourage pollutant uptake; and to uncover pollutant uptake by mature GI at the watershed-scale and inform maintenance regimes as GI ages. Such research will provide essential guidance to designers, regulators, and municipalities seeking to manage stormwater runoff through the widespread implementation of city-wide GI.

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