Infiltration Patterns Across 300 Bioswales: Influence of Watershed Size and Land Use

Modèles d'infiltration dans 300 noues de biorétention : influence de la taille du bassin versant et de l'utilisation des terres

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RÉSUMÉ

Les noues végétalisées constituent un outil essentiel pour la gestion durable des eaux pluviales en milieu urbain, mais leurs performances hydrauliques varient fortement selon les conditions locales. Cette étude évalue environ 300 bioswales implantées à New Haven afin d'analyser comment la taille du bassin versant, l'occupation du sol, la végétation et les dépôts sédimentaires à l'entrée influencent les taux d'infiltration mesurés in situ. Les bassins versants ont été délimités manuellement dans un SIG en interprétant le sens d'écoulement de surface. Les tests d'infiltrométrie montrent des infiltrations nettement plus faibles à l'entrée (médiane ≈ 3,5 cm/min) qu'à la sortie (≈ 5 cm/min). Une corrélation faible mais significative entre la taille du bassin versant et l'infiltration (ρ ≈ 0,12) a été observée—un résultat surprenant compte tenu des charges polluantes plus élevées attendues dans les grands bassins. Les zones résidentielles présentent des infiltrations supérieures à celles des zones commerciales. Ces résultats, obtenus sur un ensemble de sites plus vaste que dans la plupart des études existantes, fournissent une base solide pour optimiser l'implantation et l'entretien des infrastructures vertes.

ABSTRACT

Bioswales play a major role in managing roadway runoff, yet their hydrologic performance varies widely. This study analyzes approximately 300 roadside bioswales in New Haven, Connecticut, the largest dataset of its kind to our knowledge, to quantify how watershed size, land-use setting, vegetation cover, and inlet sedimentation influence infiltration capacity. Watersheds were manually delineated using GIS-based flow interpretation, and double-ring infiltrometer tests were conducted at each inlet and outlet. Inlet infiltration was consistently lower, with a median initial rate of 3.5 cm/min, compared with 5.0 cm/min at outlets, reflecting sediment and pollutant accumulation from roadway runoff. Land-use differences were substantial: residential bioswales showed higher median infiltration (≈4.45 cm/min) than commercial systems (≈4.00 cm/min). Surprisingly, infiltration increased modestly with watershed size ($\rho \approx 0.12$, $p < 0.001$), contrary to the expectation that larger watershed loads would increase clogging and reduce hydraulic conductivity. Vegetation had a positive but modest influence ($\rho \approx 0.10$–0.11). These city-scale findings demonstrate that bioswale performance emerges from interacting influences of watershed loading, land-use pressures, and inlet sedimentation rather than design differences, offering guidance for future planning of green-infrastructure networks.

KEYWORDS

Bioswale, infiltration, land use, watershed area

1 INTRODUCTION

Urban bioswales are widely implemented to intercept roadway runoff, promote infiltration, and reduce hydraulic loading on stormwater networks. Although the design specifications across New Haven's ~300 bioswales are essentially identical, site conditions differ dramatically, watershed sizes range from ~80 m² to over 2400 m², land-use settings include residential, commercial, and mixed-use corridors, and sediment delivery varies strongly with traffic intensity and street geometry. These differences produce substantial variation in hydrologic performance, even among bioswales constructed with the same underlying design. Prior studies typically evaluate far fewer installations, often <20 bioswales, limiting generalizability (Brown & Hunt, 2023; Kondratenko et al., 2024). By contrast, this study evaluates ≈300 bioswales, advancing the science by examining full-city hydrologic variability. Sediment accumulation at bioswale inlets is widely recognized as a primary cause of reduced infiltration (Kong et al., 2021; Qin et al., 2019). Land-use context also influences sediment loads, compaction, and vegetation health (Qin et al., 2019; Li et al., 2020). Vegetation is known to improve soil structure and hydraulic function (Wu et al., 2022). This study integrates these factors to determine which most strongly shape bioswale infiltration across a municipal system.

2 METHODS

Watersheds were delineated manually in GIS by interpreting roadway slopes, curb geometry, and gutter flow paths to determine how runoff reached each bioswale inlet. This manual approach allowed accurate handling of micro-topographic features such as driveway aprons and curb breaks. Infiltration was measured with a Turf-Tec double-ring infiltrometer at both the inlet and outlet of each bioswale. Four measurements per site (two inlet, two outlet) were collected, yielding over 1,000 infiltration tests across the 300 bioswales (Figure 1) . Initial, final, average, and saturated infiltration rates were calculated from depth–time curves. Vegetation cover was assessed by dividing each bioswale into four equal longitudinal quarters from inlet to outlet. In each quarter, vegetative cover was visually estimated on a 0–100% scale. Non-parametric statistics (Wilcoxon, Kruskal–Wallis, Spearman correlations) were used due to the non-normal distribution of infiltration data.

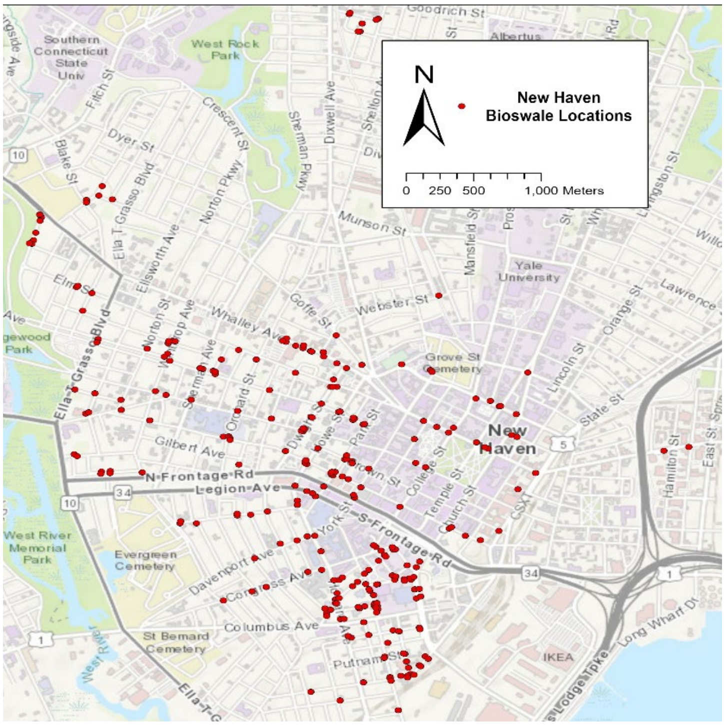

Figure 1. City of New Haven bioswale locations.

3 RESULTS

Across the 300 bioswales, infiltration was consistently lower at inlets than outlets. Median initial infiltration was

3.5 cm/min at inlets and 5.0 cm/min at outlets, with similar differences for average and saturated rates. These patterns indicate that sediment accumulation at curb openings is the dominant cause of reduced infiltration, while deeper soils remain relatively consistent between inlet and outlet areas.

Watershed area ranged from ~80 to >2400 m², and infiltration increased modestly with watershed size for all stages ($\rho \approx 0.11$–0.13, $p < 0.001$) (Figure 2). Although the effect is weak, the trend was surprising: larger watersheds were expected to deliver more pollutants and fine sediments, potentially reducing infiltration. Instead, the slight increase suggests that more frequent hydrologic loading may disrupt clogging layers, or that watershed size alone is less influential than localized inlet sedimentation.

Figure 2. Watershed size vs infiltration.

Land-use differences were more pronounced than watershed effects (Figure 3). Residential bioswales had the highest infiltration rates (median initial ≈ 4.45 cm/min), while commercial corridors showed notably lower rates (≈ 4.00 cm/min). Mixed-use areas fell in between. The results align with expectations that higher vehicular activity and sediment delivery in commercial areas suppress infiltration.

Vegetation showed a modest positive correlation with infiltration ($\rho \approx 0.10$–0.11). Bioswales with greater vegetative cover tended to infiltrate slightly faster, reflecting improved soil structure and macroporosity. However, vegetation effects were consistently smaller than land-use and inlet-sedimentation effects.

Localized sedimentation at the inlet is the strongest control on infiltration, followed by land-use intensity, with vegetation playing a secondary role. Watershed size influences performance only weakly, indicating that the primary drivers of infiltration variability are related to site-level sediment delivery and urban context, not differences in design.

Figure 3. Land use vs infiltration.

4 DISCUSSION

Inlet sedimentation is the dominant control on infiltration across New Haven's network. Despite identical design, bioswales experience highly uneven watershed loading and land-use pressures. Larger watershed areas unexpectedly showed slightly higher infiltration, potentially due to repeated hydrologic disturbance reducing crust formation. Commercial areas consistently exhibited lower infiltration due to greater pollutant and sediment loads. Vegetation contributed positively but was secondary to soil and sediment dynamics.

5 CONCLUSIONS

Bioswale infiltration performance in New Haven is shaped by watershed loading, sedimentation, land use, and vegetation. Targeted inlet maintenance and watershed-aware siting can improve long-term performance.

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