Enhancing Life cycle assessment (LCA) of bioretention systems by including functional benefits - Case studies in Quebec (Canada)

Améliorer l'analyse du cycle de vie (ACV) des systèmes de biorétention en intégrant les bénéfices fonctionnels – cas d'études au Québec, Canada

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RÉSUMÉ

Cette étude applique la méthodologie d'analyse du cycle de vie (ACV) afin d'évaluer les impacts environnementaux des systèmes de biorétention à partir d'études de cas réalisées au Québec, Canada. Les cas étudiés comprennent des stationnements imperméables et des rues résidentielles larges, tous intégrant des systèmes de biorétention pour la gestion des eaux pluviales urbaines. Les frontières de l'ACV incluent les matériaux, la construction, l'entretien, l'opération ainsi que la fin de vie. Une innovation clé de cette recherche réside dans l'intégration des bénéfices fonctionnels des systèmes de biorétention, tels que l'amélioration de la qualité de l'eau, la réduction des débits de pointe et l'atténuation des îlots de chaleur urbains, au sein du cadre de l'ACV, afin de compléter l'évaluation traditionnelle centrée sur les impacts. Les objectifs de l'étude sont de quantifier les impacts (issus de matériaux, de la construction, de l'entretien et de la fin de vie) et les bénéfices, d'évaluer la précision des données et de réaliser des analyses d'incertitude et de sensibilité pour combler les lacunes, notamment le manque de données de performance, les incohérences dans les paramètres de conception et la variabilité des pratiques d'entretien. Les résultats permettront d'optimiser la conception et de soutenir une prise de décision plus éclairée pour des systèmes de biorétention plus durables.

ABSTRACT

This study applies life cycle assessment (LCA) methodology to evaluate the environmental impacts of bioretention systems through case studies in Quebec, Canada. The case studies include impervious parking lots and wide residential streets, all integrating bioretention systems for urban stormwater management. The LCA boundaries encompass materials, construction, maintenance, operation, and end-of-life phases. A key innovation of this research is the integration of functional benefits of bioretention systems, such as improved water quality, reduced peak flows, and mitigation of urban heat islands, into the LCA framework to complement the traditional impact-focused assessment. The objectives of the study are to quantify both impacts (from materials, construction, maintenance, and end-of-life) and benefits, assess data accuracy, and perform uncertainty and sensitivity analyses to address gaps, including limited performance data, inconsistencies in design parameters, and variability in maintenance practices. The findings will help optimize design and support more informed decision-making for sustainable bioretention systems.

KEYWORDS

Bioretention, Green Infrastructure, Environmental Impacts, Life Cycle Assessment, Stormwater Management

1 INTRODUCTION

Urbanization has led to increases in urban flooding, surcharge of storm drains, and decrease in surface water quality. Aging and deteriorating infrastructure are also exacerbating the challenges of stormwater management in urban settings. Municipalities are impacted by climate change, and they often lack the ability to implement enough mitigation measures to prevent damages. The development and application of green infrastructure (GI), including bioretention systems, has been gaining ground due to the benefits they offer. Bioretention systems manage rainwater by providing temporary storage of runoff flows and allowing water to infiltrate through the soil layers. These systems are typically comprised of a few layers that function collectively to manage stormwater runoff. The bottom layer is composed of coarse aggregate or granular material, with or without an underdrain, and serves as an underground storage. Above this layer is an engineered soil media to sustain vegetation growth, and filter fine pollutants and nutrients. The surface is vegetated, allowing the root system to maintain the infiltration capacity of the soil media. The surface also allows temporary ponding and may include an overflow outlet to safely convey excess flows to the downstream storm sewer system. In some configurations, an inlet structure is provided to capture larger particles before the runoff enters the system. Benefits of bioretention systems can include reduced impacts from flooding, improved water quality, increased biodiversity, and reduced heat-island effect.

Life cycle assessment (LCA) is a methodology used to measure the environmental impacts of a product, service or infrastructure over its entire life cycle. It can identify opportunities to use better materials, improve maintenance practices, reduce energy consumption, and guide decision makers towards improving sustainability. Several studies have compared bioretention systems and other GI to conventional grey infrastructure, with LCA results generally favoring GI for their lower environmental impacts (Bhatt et al., 2019; Brudler et al., 2019; Tang et al., 2023; Wang et al., 2013). Comparative analyses between bioretention systems and alternatives such as permeable pavements or vegetated swales indicate that bioretention often perform better environmentally (Tang et al., 2023). Kumar et al. (2024) analyzed 8 configurations of bioretention systems and found that media choice significantly affects impacts, primarily due to transportation distances and resource extraction. Similarly, Sagrelius et al. (2022) compared 4 types of bioretention systems in 11 different configurations and concluded that designs incorporating large quantities of concrete and long transportation distances had the highest environmental impacts. In another study, X. Xu & Zhang (2019) conducted an LCA on 7 bioretention design scenarios to optimize nutrient filtration performance. Despite these contributions, existing research predominantly focuses on life cycle burdens, such as material production and construction, while neglecting the potential benefits of bioretention systems. This omission represents a knowledge gap, as integrating these benefits into LCA framework could enhance bioretention design and improve the overall sustainability of stormwater management.

2 METHODOLOGY

2.1 Case studies

Building on the knowledge gained and available data from partner municipalities, a total of 6 case studies were identified to conduct this research. These include 3 wide residential streets and 3 impervious parking lots with bioretention systems for the management of stormwater runoff in the province of Quebec, Canada. Two initial case studies were considered in this analysis.

2.1.1 Case Study 1: Roland-Beaudin Parking Lot, Quebec City, Quebec

Constructed in 2020, the study section of the re-constructed parking lot covers 4500 m^2 and was designed to infiltrate a 6-mm rainfall, treat water from a 26-mm rainfall, and retain runoff for a 1:100 yr rainfall (from "future climate" IDF curves, which take into accounts climate change) with a release rate of 15 L/s/ha to the municipal network. The GI system includes bioretention systems, vegetated ditches, and underground storage. Documentation available for this project includes a design report, construction drawings, tender documents, and a maintenance report.

2.1.2 Case Study 2: Pierre-Laporte Parking Lot, Victoriaville, Quebec

Constructed in 2020, the 9000 m^2 parking lot was designed to limit the stormwater runoff flows to 50 L/s/ha for a 1:25 year rainfall event (with a 10% increase to reflect climate change projections) and achieve 80% removal of total suspended solids and 40% reduction in phosphorus concentration. GI incorporated in the project include

vegetated swales, bioretention systems and permeable pavement. The project also includes underground storage and a hydrodynamic separator. Documents available for this project include a design report, construction drawings and tender documents.

2.2 Research objectives

The goal of the LCA study is to quantify and compare the environmental impacts and benefits of the bioretention systems for each case study. The scope of the LCA adopts a cradle-to-grave perspective, encompassing all life cycle stages: materials (ex: gravels, filter media, vegetation, concrete) and transportation, construction (construction activities), maintenance (e.g. regular inspections, removal of sediments, vegetation management), operation (operational benefits) and end-of-life (disposal). Additional benefits such as water quality improvement, peak flow reduction, increased biodiversity and heat island reduction will be evaluated for consideration in the LCA. Defining the functional unit is required to enable meaningful comparisons between scenarios. This study will compare multiple functional units such as per the impervious surface treated and per the quantity of water treated. Previous studies have commonly defined functional units based on quantity treated (Bixler et al., 2019; dos Santos et al., 2021; Peterson et al., 2021; Wang et al., 2013) or impervious surface managed (Bhatt et al., 2019; Brudler et al., 2019; Ishaq et al., 2023; Sagrelius et al., 2022; C. Xu et al., 2021).

The inventory phase of the LCA requires comprehensive and high-quality data across all life-cycle stages. As such, this research looks at:

(1) Quantifying the environmental impacts of bioretention systems using case study projects located in Quebec, Canada;

(2) Assessing the accuracy and representativeness of the data required to complete the inventory phase of the LCA;

(3) Conducting sensitivity analyses to identify critical data gaps and prioritize efforts for improving data quality and precision.

3 CHALLENGES AND EXPECTED RESULTS

Challenges in implementing an LCA for bioretention systems can include:

- Data availability: the completeness and reliability of inventory data vary significantly between projects and are particularly complex for bioretention systems. While partner municipalities have provided construction drawings, each project has a different layout and cross section design of the bioretention systems. It is also unclear if design drawings were followed for projects without as-built drawings.
- Differing design parameters: the case studies differ substantially in design criteria, with no standardized approach across projects. For example, one bioretention system was constrained by available space within the street right-of-way without considering runoff volume capacity, whereas the two parking lot case studies were designed to manage different rainfall events. These discrepancies complicate comparative analysis and warrant testing for different functional units.
- Differing designs and materials: each project is designed differently with different materials comprising the bioretention systems. The challenges reside in properly linking each material and each activity to the LCA database.
- Maintenance schedules: maintenance practices differ across projects and across municipalities. This can affect long-term performance of each bioretention system, but also impact LCA results (Jean et al., 2023).
- Lack of performance data and/or field measurements: a lack of field measurements and monitoring data hinders accurate evaluation of hydrological and pollutant removal performance, complicating the LCA analysis.

Ultimately, the study compares results across case studies, performs uncertainty analyses by varying critical parameters, and quantifies the environmental benefits of bioretention systems from a life cycle perspective.

4 CONCLUSION

LCAs evaluate impacts of bioretention systems across all life-cycle stages. This study not only quantifies these

impacts but also incorporates the benefits of bioretention systems into the assessment, creating a more holistic and comprehensive life cycle model that reflects both burdens and benefits. A critical component of the analysis will be the evaluation of data quality and completeness required to build the LCA inventory. By performing uncertainty and sensitivity analyses, the study will determine the robustness and accuracy of the results, identify key data gaps, and prioritize areas for improvement. Comparing results from case studies will help identify best practices and guide design optimization. It will contribute to documenting the performance and design considerations of bioretention systems in Nordic climates, with a specific focus on Quebec, Canada.

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