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**Auteurs:** Pierremann-Fils Pierre, Rose-Michelle Smith, Samuel Pierre, & Musandji Fuamba

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# Implementation of a Maintenance Plan for Stormwater Management Infrastructures Using the Systemic Method

Pierreman-Fils Pierre<sup>1,2</sup>, Rose-Michelle Smith<sup>1,2</sup>, Samuel Pierre<sup>1,2</sup>, and Musandji Fuamba<sup>1,2</sup>

<sup>1</sup> Polytechnique Montréal, Montréal, Canada

<sup>2</sup> Institut des Sciences, des Technologies et des Études Avancées d'Haïti, Milot, Haïti

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## ABSTRACT

Urban stormwater management is essential for limiting flooding, protecting ecosystems and ensuring infrastructure durability. However, the long-term effectiveness of these systems depends heavily on an appropriate maintenance strategy. This paper develops a preventive maintenance plan based on a systemic approach, aimed at enhancing the sustainability and performance of stormwater management infrastructures, particularly bioretention basins. The approach adopted breaks down each infrastructure into critical sub-components, assesses their performance according to specific criteria, and then recommends maintenance actions based on observed results. A case study of four basins in Montréal revealed performance levels ranging from 83.21% to 85.23%, indicating the need for regular inspections, continuous monitoring, and a medium priority for intervention. The results support the effectiveness of the systemic method for prioritizing interventions and anticipating deterioration, ensuring optimal and sustainable infrastructure management. This research proposes a structuring framework, offering municipal managers a decision-making tool tailored to address the growing challenges posed by urbanization and climate change. It demonstrates the practical effectiveness of the systemic approach in an operational urban stormwater context.

# 1. INTRODUCTION

Stormwater management infrastructures play a fundamental role in preventing urban flooding and protecting water quality in the context of urbanization and climate change (Andrieu et al. 2017; Gougeon et al. 2023; Moravej et al. 2025; Oppliger et al. 2023; Sebti 2016). These solutions are known under different names depending on the country, the water management objective, and the application context (Fletcher et al. 2014).

Bioretention basins, also known as rain gardens, are shallow landscaped depressions that are filled with vegetation and engineered soil. Their purpose is to collect and treat stormwater runoff from small contributing surfaces (MDDEFP 2014). To transfer infiltrated water to the storm or combined sewer network, certain bioretention systems might have a perforated underdrain. To prevent soil erosion, improve water retention, encourage vegetation growth, and aid in the breakdown of organic matter, they are frequently covered with a layer of mulch (Maisonneuve 2021). However, their long-term effectiveness depends on the implementation of a rigorous maintenance plan designed to preserve hydraulic performance, ensure pollutant removal, and prevent functional degradation (Sauvé et al. 2014). Inadequate maintenance can lead to a reduction in hydraulic and purification performance, thereby increasing environmental and structural risks (Verge 2020).

The systemic approach provides a robust framework for assessing long-term maintenance conditions of these infrastructures within complex urban environments where fragmentation of land use disrupts the natural hydrological cycle (Néel et al. 2016). This approach facilitates the integration of multiple components and interactions within the system to gain a better understanding of their long-term functioning (Flaux 2017). Thus, a maintenance strategy based on a systemic approach can guarantee the sustainability and efficiency of stormwater management structures in an urban context, including bioretention.

The main objective of this study is to establish an effective maintenance strategy for stormwater management structures in an urban environment, particularly bioretention basins. Specifically, this research aims first to decompose a stormwater management structure into its various components using a systemic approach. Second, it seeks to assess the current performance of the structure according to pre-established criteria. Performance assessment is conducted not as an end itself, but as a basis for establishing a preventive maintenance strategy. Finally, the study will propose an appropriate maintenance plan to prevent potential failures.

This study is based on the analysis of four bioretention basins located on Papineau Avenue in Montréal. These basins, identified under the codes B-21-22-23-M8, B-31-32-M9, B-29-30-M10 and B-33-34-M11, constitute a representative sample for the application of a

systemic maintenance methodology. The four monitored bioretention basins drain a combined area of about 0.2 ha ( $\approx 2,000 \text{ m}^2$ ).

To give a visual representation of the location and its urban setting, Figure 1 shows an example of one of the basins under study (B-29-30-M10).



Figure 1 Example of a bioretention basin (B-29-30-M10) located along Papineau Avenue, Montréal.

*Source: Adapted from Maisonneuve (2021), image extracted from Google Earth.*

## 2. METHODOLOGY

The methodology adopted for this study is based on a systemic approach integrating several stages to assess the maintenance conditions of bioretention basins. The methodology consists of several phases: identification of system components, performance evaluation according to specific criteria, development of a structured maintenance plan and proposal of intervention strategies. By integrating these stages, the systemic approach enables us not only to diagnose potential failures but also to suggest maintenance practices through proactive and adaptive infrastructure management.

### 2.1 Identification of system components

Each bioretention pond is broken down into various sub-components, including stormwater storage capacity, infiltration capacity, vegetation condition, hydrocarbon contamination, sediment contamination and heavy metal contamination. As shown in Figure 2, a logical representation of the interactions between these components is created to enhance the understanding of their interdependence.

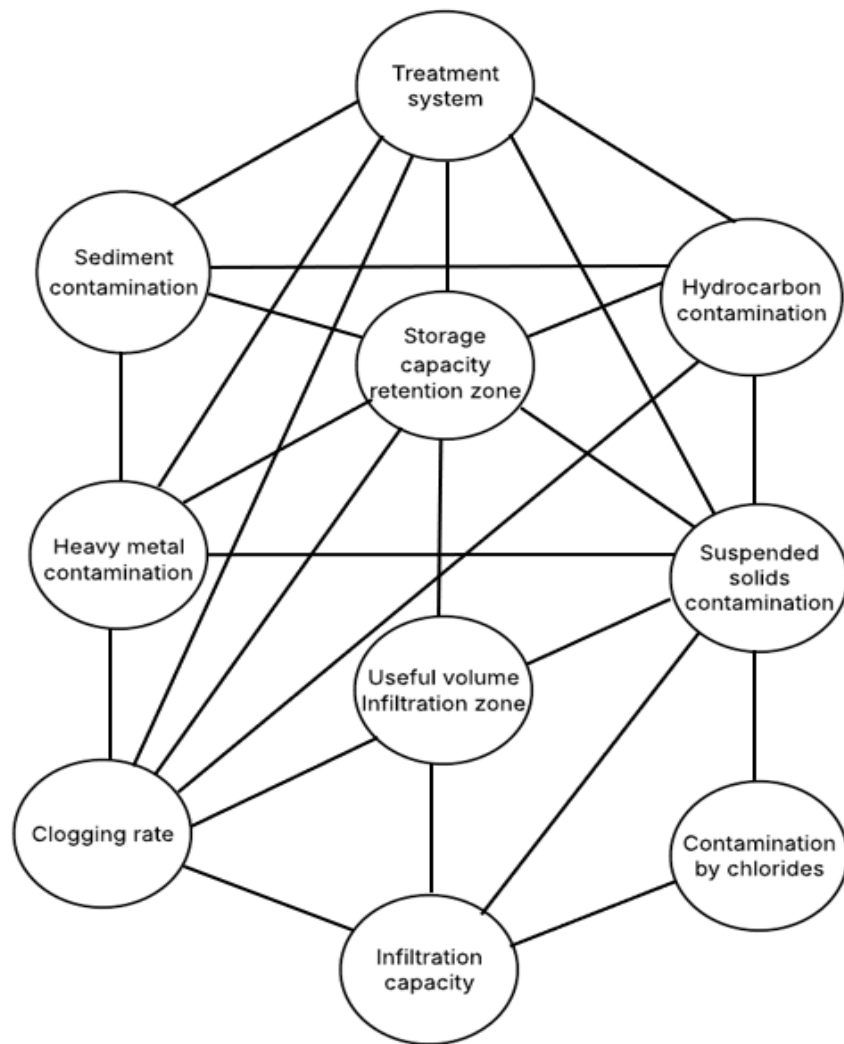


Figure 2 Conceptual systemic diagram of the system, illustrating the main components and their qualitative interactions.

Figure 2 illustrates the systemic interactions between performance indicators and influencing factors in stormwater best management practices (BMPs). Treatment systems are directly connected to storage capacity, suspended solids contamination, and hydrocarbon contamination, reflecting their dual role in hydraulic retention and pollutant removal. The storage and retention zone is central within the system, linking to useful infiltration volume, infiltration capacity, and multiple contaminant pathways, including sediments, heavy metals, hydrocarbons, suspended solids, and chlorides. The useful infiltration volume directly regulates infiltration capacity while being affected by clogging processes that progressively reduce available storage and percolation potential. Infiltration capacity is connected to clogging rate, useful volume, and chloride contamination, highlighting its sensitivity to both physical obstruction and chemical stressors. The clogging rate represents the cumulative effect of sediment deposition, heavy metal accumulation,

and infiltration decline, indicating the loss of soil porosity over time. Sediment and heavy metal contamination are strongly interrelated, as fine particles act as carriers for metals, enhancing their retention in the filtering media. Similarly, hydrocarbons and suspended solids are mutually connected through co-transport mechanisms. Chloride contamination further exacerbates clogging and suspended solids accumulation by altering soil structure and reducing hydraulic conductivity. Altogether, these interactions demonstrate the systemic nature of BMP performance, where multiple hydrological and physico-chemical pathways converge to drive maintenance needs and long-term functionality.

## 2.2 Assessment of current performance

To evaluate the runoff retention rate, in accordance with the law of continuity, Equation 1 proposed by Khan et al. (2012) is recommended.

$$V = \left(1 - \frac{V_{out}}{V_{in}}\right)100\% \quad (1)$$

Where:

- $V$  = reduction in runoff volume (%),
- $V_{out}$  = volume of runoff leaving the BMP during the rainfall event ( $m^3$ ), and
- $V_{in}$  = volume of runoff entering the BMP during the rainfall event ( $m^3$ ).

To evaluate peak flow reduction as a performance indicator, Equation 2 from Khan et al. (2012) is used.

$$P_{pf} = \left(1 - \frac{Q_{out}}{Q_{in}}\right)100\% \quad (2)$$

Where:

- $P_{pf}$  = reduction in peak flow (%),
- $Q_{in}$  = maximum runoff flow entering the BMP during an event ( $m^3/s$ ), and
- $Q_{out}$  = maximum rate of runoff leaving the BMP during an event ( $m^3/s$ ).

To evaluate the performance in response to small rainfall ( $P_{sr}$ ), Equation 3 is applied:

$$P_{sr} = \left(\frac{N_{effective}}{N_{total}}\right)100\% \quad (3)$$

Where:

- $N_{effective}$  = number of rainfall events with a return period of less than one year that were successfully managed by the system, meaning that no overflow occurred and all inflow was infiltrated or retained on site within the same day of the rainfall event, and

$N_{total}$  = total number of such events observed. This reflects the system's responsiveness to small, frequent rains.

Small and frequent rains are considered equivalent to small rainfall events, defined as having an intensity greater than a trace but not exceeding 2.5 mm/h and a return period of less than one year. This definition follows USEPA (2021) recommendations, which emphasize the importance of evaluating basin performance under frequent minor events. Although these storms are often overlooked compared to extreme events, they account for a significant share of the annual runoff volume. Assessing the capacity of BMPs to manage them effectively is therefore essential to evaluate their overall responsiveness and maintenance needs.

In this study, small and frequent rainfall events defined as having an intensity greater than a trace and not exceeding 2.5 mm/h, with a return period of less than one year, and are used to assess the operational performance of BMPs under recurrent hydrologic conditions.

These events are associated with the  $P_{sr}$  indicator and represent the actual functional behavior of the system during routine rainfall conditions. In contrast, the 19 mm rainfall depth corresponds to the regulatory criterion established by the City of Montréal, which requires stormwater infrastructures to fully retain or infiltrate any rainfall event equal to or below 19 mm on site. This regulatory threshold is therefore not used to characterize small rainfall events, but rather to evaluate compliance with municipal design objectives under standardized performance conditions. This distinction makes it possible to capture both the operational performance under frequent rainfall conditions and the compliance with design requirements.

This equation is inspired by USEPA (2021) recommendations, where the agency insists on the need to verify basin behavior after each rainfall event. In the context of green infrastructure management, performance cannot be judged solely based on extreme events. It is essential to assess the system's reactivity to frequent small rainfall events, which are often overlooked but responsible for a significant proportion of annual volumes. The proposed formula quantifies this capacity by measuring the percentage of such events managed effectively (without overflow or stagnation), in accordance with the objectives defined in USEPA guidelines.

To evaluate the infiltration performance ( $P_{inf}$ ), Equation 4 is applied:

$$P_{inf} = \left( \frac{K_t}{K_0} \right) 100\% \quad (4)$$

Where:

$K_0$  = initial infiltration rate (cm/h), and

$K_t$  = infiltration rate measured at later inspection times over the lifetime of the facility, relative to  $K_0$ .

A declining  $P_{inf}$  therefore indicates progressive clogging of the filter media. Values below 0.5 may signal severe loss of infiltration capacity, requiring media rehabilitation. This threshold is justified because it marks the operational limit at which the system can no longer fully infiltrate small and frequent storm events, which represents the primary design function of bioretention practices. When this capacity is no longer sustained, it indicates that clogging has progressed to a level that impairs the intended hydrologic performance of the facility. This threshold is not a regulatory standard, but a functional reference based on observed degradation patterns in infiltration performance under operational field conditions.

These indicators were computed for a representative set of events and through field inspections. They provide both a hydrologic and operational assessment of the basin. The maintenance plan is then adjusted accordingly to preserve high performance over time and ensure functionality during both frequent and intense rainfall.

This simple equation is inspired by the discussion of Davis et al. (2009) on the progressive clogging of filter media as a critical factor in the diminishing performance of bioretention basins. Although the paper does not propose a quantitative formula, it suggests monitoring the evolution of permeability to anticipate functional loss. The ratio  $K_t/K_0$  can thus be used to quantify the degree of clogging, and guide preventive maintenance decisions (substrate replacement, aeration, etc.).

The total performance ( $P_t$ ) is evaluated using Equation 5, which incorporates all the partial performances.

$$P_t = \frac{w_1 \cdot P_{pf} + w_2 \cdot P_{sr} + w_3 \cdot P_{inf}}{w_1 + w_2 + w_3} \quad (5)$$

Where:

$w_1 - w_3$  = relative weights assigned to each criterion, according to their importance in the design or purpose of the project.

The approach adopted to assess total technical performance aligns with the work of Le Cauchois et al. (2025), who evaluated the effects of bioretention systems using hydrological and qualitative indicators, such as reductions of runoff volumes, peak flows, and pollutant concentrations. Their methodology is mainly based on input/output analysis, reinforced by SWMM modeling. However, their evaluation framework remains focused on point or simulated efficiency measurements, without integrating an evolutionary vision of performance or an operational maintenance strategy. The present study distinguishes itself

by adopting a systemic approach, considering not only immediate hydraulic efficiency but also component degradation dynamics (infiltration, clogging, vegetation, etc.) and differentiated maintenance requirements. Equation 5 thus enables a weighted aggregation of several performance dimensions, including the management of small rainfall, which are often underestimated in traditional approaches.

### Bioretention performance criteria

As shown in Table 1, current performance is assessed according to specific criteria defined in the scientific literature. Basin performance is quantified based on monitoring data and compared with corresponding performance thresholds that indicate the level of maintenance required from immediate repair to continuous monitoring or routine observation, under a temperate-cold urban climatic context (reference: Papineau, Montréal).

**Table1 Performance criteria for bioretention basins.**  
(Schueler 2008; Lloyd et al. 2002; Dietz and Clausen 2006).

| Infrastructure | Performance criteria |             |             |
|----------------|----------------------|-------------|-------------|
|                | Minimum (%)          | Average (%) | Maximum (%) |
| Bioretention   | 73                   | 81.5        | 99          |

The performance thresholds presented in Table 1 are empirical ranges derived from the scientific literature on bioretention. They are used here for illustrative purposes as part of a technical performance evaluation referential. Contrary to assertions in earlier versions, Schueler (2008) does not explicitly propose minimum or maximum performance. Instead, he presents observed performances based on the presence or absence of underground drains. In his surveys, values typically vary between 40% and 80%, depending on the type of structure and local conditions. Most importantly, this work highlights the variability of the results, justifying a cautious contextualization of the thresholds used, meaning that they should be interpreted as indicative benchmarks and adapted to site-specific factors such as soil conditions, drainage configuration, design features, and maintenance levels rather than applied as rigid standards.

The threshold values in Table 1 are based on a critical selection of empirical studies deemed representative:

- 73% as the minimum performance is based on the results of Lloyd et al. (2002) for bioretention basins with drains.
- 99% as the maximum performance (Dietz and Clausen 2006), who observed this retention level for well-designed and well-maintained bioretention basins.

- The average value of 81.5% is derived from observed operational performance rather than from an arithmetic calculation between the minimum and maximum thresholds. Rather, it represents an indicative average based on empirical observations reported in the scientific literature. Field studies conducted on stabilized and properly maintained bioretention systems, such as the study by Bond (2020) in Montréal, have reported average hydrologic efficiencies of approximately 84%. These results support the use of 81.5% as a representative reference value to characterize the typical performance of bioretention infrastructures under real operating conditions.

It is important to stress that these thresholds were selected for their severity and frequency of occurrence in field studies in urban environments with similar issues (Ermilio 2005; Rushton 2002; Van Seters et al. 2006). Among the literature reviewed, some works (Sharkey 2006) report significantly lower performance levels ranging from 20% to 50%, particularly for poorly maintained systems or those in the early stages of operation. Such cases were excluded from our reference range, as they do not reflect the expected behaviour of stabilized and monitored infrastructures, such as those on Papineau Avenue.

In this study, the thresholds presented in Table 1 are used as indicative reference points to interpret the performance criteria. Values close to the minimum threshold indicate the need for corrective or rehabilitative actions; values around the average threshold reflect satisfactory functioning that requires continuous monitoring; and values near the maximum threshold denote optimal performance, where only routine observation is necessary.

Finally, these thresholds should be understood as guide values that place the observed technical performance within a realistic range, rather than as normative criteria. This framework can be adjusted in other studies according to local specificities, functional objectives, and temporality. In practice, such adjustments should consider local site conditions (e.g., soil type, climate, hydrology), the functional objectives defined by the municipality (e.g., peak flow reduction, pollutant removal, resilience targets), and the temporal scale, including the maturity of the system and its monitoring history.

On this basis, the maintenance needs are directly inferred from the thresholds in Table 1 (and 2): values < 73% call for urgent rehabilitation, values in the 73–85% range require regular inspections and procedural updates, and values > 85% justify routine observation.

The reference framework of Table 1 is expanded to accommodate various operational and climatic conditions by the modified thresholds shown in Table 2. These threshold values are the outcome of a process-based conceptual framework that considers how operational and climatic stressors affect the internal functioning of bioretention systems, rather than

being drawn from a single empirical dataset. Infiltration capacity, clogging dynamics, and hydraulic response are all altered by variables like rainfall variability, road-salt inputs, and freeze-thaw cycles, as several studies have shown (Davis et al. 2009; Gougeon et al. 2023; Roy-Poirier et al. 2010). The USEPA's (2021) recommendations, which stress the need to tailor performance indicators to local environmental conditions, are in line with this interpretation. The Wet Weather Flow Management Guidelines of the City of Toronto (2006) take a similar adaptive stance, stating that performance goals should be interpreted loosely and modified in accordance with regional operational and climatic circumstances. Therefore, rather than being set normative values, the thresholds in Table 2 are suggested as adaptive analytical benchmarks. The equilibrium between renewal processes (like infiltration recovery, vegetation regeneration, and substrate aeration) and degradation processes (like clogging, compaction, or chemical contamination) determines basin performance from a systemic standpoint. Depending on operational and climatic limitations, this balance changes in different ways.

**Table 2 Adjusted performance thresholds according to climatic and operational context.**

| Climatic /Operational context           | Performance criteria |             |             |
|-----------------------------------------|----------------------|-------------|-------------|
|                                         | Minimum (%)          | Average (%) | Maximum (%) |
| Temperate humid, separated sewer system | 75                   | 83          | 98          |
| Tropical or subtropical humid climate   | 68                   | 80          | 96          |
| Semi-arid or arid climate               | 72                   | 85          | 98          |

The thresholds shown in Table 2 are conceptual benchmarks based on performance ranges reported in North American stormwater guidance documents, such as the USEPA guidance for arid and semi-arid regions, the Minnesota Stormwater Manual (climate cold/temperate), and the Chesapeake Stormwater Design Specification No. 9 (humid subtropical/tropical). They are not derived from a single guideline. The adaptive thresholds used in this study are supported by these sources, which show that BMP performance varies greatly depending on operational and climatic conditions.

Degradation is slowed in temperate humid regions with separated sewer systems because there are no freeze-thaw or salt-related stressors. The slightly higher expected performance (75%, 83%, 98%) results from the more even distribution of hydraulic loads throughout the year. Rainfall is more common in tropical or subtropical regions as brief, heavy downpours. Here, rapid surface saturation and transient overflow, rather than clogging, limit infiltration. Therefore, rather than system inefficiency, the lower thresholds (68%, 80%, and 96%) reflect hydrologic constraints. Although rainfall is rare in semi-arid and arid environments, the dry, porous substrate frequently results in high initial infiltration rates. Long dry spells,

however, cause surface sealing and a brief decrease in soil wettability, which lowers initial infiltration until the substrate is rehydrated. The slightly lower minimum threshold (72%) and higher average (85%) after the system stabilizes can be explained by this dynamic.

These theories are based on hydrologic reasoning, which holds that different stressors imposed by different climates have distinct effects on internal system functions. The suggested thresholds represent tenable and physically consistent performance ranges by connecting functional responses (infiltration, retention, regeneration) with physical causes (temperature variation, rainfall intensity, soil moisture regime). They reinforce the scientific soundness and systemic coherence of the suggested framework by acting as analytical standards that can be improved and empirically verified in subsequent research.

### 3. RESULTS

A systemic approach was used to assess the four bioretention basins' technical performance. The four monitored bioretention basins (B-21-22-23-M8, B-31-32-M9, B-29-30-M10, and B-33-34-M11) are situated along Papineau Avenue in Montréal, as depicted in Figure 3. The Curotte-Papineau combined sewer catchment includes this urban corridor.

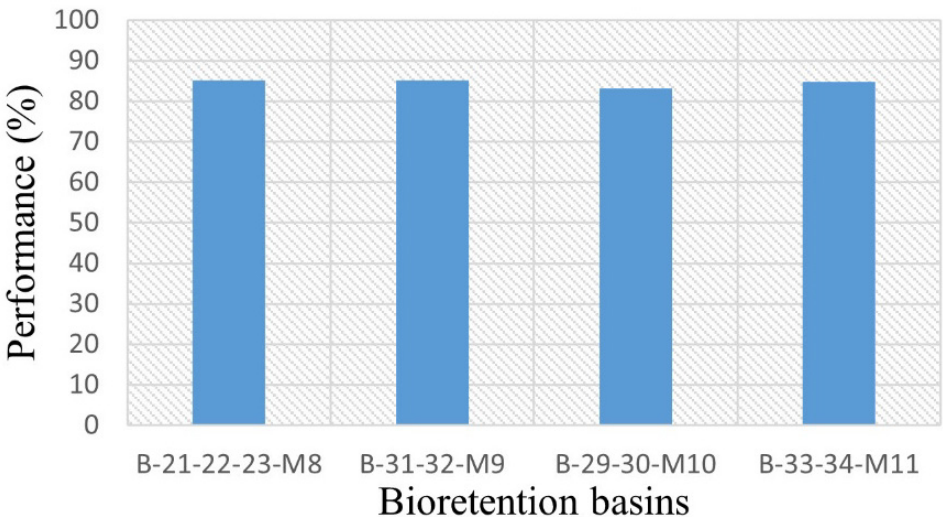


Figure 3 Performance of the four bioretention basins.

Table 3 Lists the attributes of the four bioretention basins. They perform between 83.21% and 85.23%. Table 4 presents the results in detail.

Table 3 Characteristics of the 4 bioretention basins.

| Bioretention basins | Length (m) | Width (m) | Depth (m) | $V_{in}$ (m <sup>3</sup> ) | $V_{out}$ (m <sup>3</sup> ) |
|---------------------|------------|-----------|-----------|----------------------------|-----------------------------|
| B-21-22-23-M8       | 83.71      | 3.5       | 0.78      | 1174.81                    | 4.35                        |
| B-31-32-M9          | 55.88      | 3.5       | 0.78      | 528.16                     | 55.9                        |
| B-29-30-M10         | 58.58      | 3.5       | 0.78      | 1214.77                    | 144.11                      |
| B-33-34-M11         | 55.47      | 3.5       | 0.78      | 872.46                     | 97.06                       |

In Table 3,  $V_{in}$  and  $V_{out}$  correspond to event-based volumes derived from monitoring data, i.e., the total inflow and outflow observed during the rainfall events analyzed for each basin.

Table 4 Performance of the 4 bioretention basins.

| Bioretention basins | Performance (%) |
|---------------------|-----------------|
| B-21-22-23-M8       | 85.23           |
| B-31-32-M9          | 85.18           |
| B-29-30-M10         | 83.21           |
| B-33-34-M11         | 84.79           |

The performance values in Table 4 represent the average results calculated over the monitoring period 2018–2020 on Papineau Avenue, covering approximately two and a half years of data and several dozen rainfall events. During this period, only rainfall events of 19 mm were considered, in accordance with the City of Montréal’s regulation.

The weights assigned to the performance criteria were defined to reflect the functional priorities specific to the context in which the infrastructures were installed, i.e. Papineau Avenue in Montréal. More specifically, a weight of  $w_1 = 0.4$  was assigned to the reduction of peak flows because the sector is connected to a combined sewer system, where hydraulic overloading constitutes a major risk of overflow. This priority also aligns with the municipal logic of controlling upstream volumes, as recommended in the City of Montréal Master Plan for Stormwater Management. A second weight of  $w_2 = 0.4$  was assigned to infiltration capacity due to northern climatic conditions. Indeed, the performance of bioretention cells can decline rapidly during freeze/thaw cycles due to substrate clogging, soil compaction, and road salt accumulation. Maintaining sustainable infiltration is therefore a critical issue to ensure the functional longevity of the system, as confirmed by previous performance monitoring (Autixier et al. 2014). Finally, small rainfall management, while relevant for dissolved pollutant control and slow recharge, was weighted at  $w_3 = 0.2$  to reflect its

secondary role in the project's operational priorities, which are primarily aimed at reducing critical volumes during intense events. It may be revised for other contexts where performance objectives differ (e.g., rural locations, absence of combined network, priority given to water quality). In practice, these weights are not universal and should be adapted to local conditions. For example, in regions without combined sewers, water quality may be given greater importance, while in warmer climates without freeze thaw cycles, infiltration capacity may be weighted less. This flexibility ensures that the framework can guide maintenance strategies across diverse urban and regional contexts.

The four basins with performance levels between 83.21% and 85.23% fall into the category of infrastructure requiring regular inspections, procedural updates, and performance data monitoring, as described in the methodology.

It is important to emphasize that the results obtained must be interpreted within the specific context of the study. Any change in the selection of evaluation criteria or variation in their weighting could impact the overall technical performance of the bioretention basins. Furthermore, fluctuations in individual performance for example, by modifying the number of small rainfall events considered or by adopting a different interpretation of the data could also lead to a reassessment of the overall technical performance. These considerations confirm that the framework should be applied as a flexible tool rather than a rigid standard, with adjustments made according to the functional objectives and environmental conditions of each site.

Finally, these results confirm the relevance of the systemic approach to infrastructure analysis, which facilitates the identification of targeted maintenance needs based on observed performance levels. The method enabled us not only to establish a hierarchy of intervention priorities but also to propose an appropriate maintenance plan.

## **4. DEVELOPING A MAINTENANCE PLAN**

Considering the results obtained, which highlight the relevant performance of the bioretention basins studied, it is essential to adopt a structured maintenance plan to preserve and enhance these performance levels over the long term. The proposed plan, based on a systemic approach, organizes preventive maintenance actions according to identified performance thresholds. For each measure, it provides details on the intervention frequency, priority level, specific actions required, and their technical justifications. Table 5 lists all the recommended maintenance measures to ensure the long-term durability and operational efficiency of the infrastructure.

Table 5 Maintenance plan including performance levels and justifications.

| Performance observed                          | State of the infrastructure        | Recommended actions                                                   | Priority for intervention | Technical justification                                                | References                                             |
|-----------------------------------------------|------------------------------------|-----------------------------------------------------------------------|---------------------------|------------------------------------------------------------------------|--------------------------------------------------------|
| > 90%                                         | Optimal                            | Monthly visual inspection                                             | Low                       | Ensures everything is running smoothly with no signs of deterioration. | USEPA (2016)<br>USEPA (2021)<br>Erickson et al. (2010) |
| 76%–89%                                       | Functional, but with signs of wear | Twice-yearly inspection of inlets/outlets and drainage system         | Medium                    | To prevent debris build-up, maintain infiltration rate.                | USEPA (2021)<br>USEPA (2016)                           |
| ≤ 75%                                         | Significant degradation            | Full technical inspection and immediate repairs                       | Important                 | Critical performance level, may compromise water management.           | USEPA (2021)                                           |
| Sediment or vegetation obstructing the drains | Partial to severe obstruction      | Thorough cleaning and local refurbishment once per year, if necessary | Important                 | Risk of localized flooding or water stagnation.                        | USEPA (2016)<br>USEPA (2021)                           |
| Filtering soil degradation (clogging)         | Decrease in infiltration capacity  | Filter substrate replacement or regeneration                          | Important                 | Clogging drastically reduces cell performance.                         | USEPA (2016)<br>USEPA (2021)                           |

It should be noted that the apparent difference between monthly inspections for >90% performance and twice-yearly inspections for 76–89% performance reflects a functional differentiation in maintenance: monthly visual checks (low-intensity, preventive) vs. biannual technical inspections (higher-intensity, corrective).

At high performance levels (>90%), degradation processes remain minimal, and the system is still self-regulating: infiltration, vegetation, and drainage operate near their optimal capacity. Monthly inspections in this range are therefore limited to light, visual checks intended to detect early warning signals such as surface sediment accumulation, localized clogging, or vegetation stress before any measurable decline occurs. These preventive observations are justified by the non-linear nature of degradation in stormwater systems, where minor disturbances can rapidly escalate into functional losses if not addressed

promptly. Preventive monitoring thus acts as a low-intensity feedback loop, maintaining system stability with minimal intervention cost.

In contrast, the twice-yearly inspections recommended for basins with 76–89% performance correspond to corrective technical interventions. These systems already exhibit partial wear, requiring focused examination of hydraulic structures, inlets, and outlets to remove accumulated sediments and restore infiltration capacity. Such inspections are more resource-intensive, involving specialized equipment and partial access to subsurface components, which justifies a lower frequency. From a systemic perspective, this second level of maintenance represents a higher-intensity corrective loop aimed at re-establishing equilibrium once degradation has begun to alter the system's performance.

Accordingly, the differentiation in inspection frequency is not arbitrary but grounded in the systemic behavior of the infrastructures: preventive monitoring dominates in the stability domain, while corrective maintenance is triggered in the controlled degradation domain.

The last two items in Table 5 (drain obstruction and filter media clogging) are not performance objectives, but operational issues identified during field inspections. They are assessed qualitatively rather than through monitoring indicators, in line with USEPA guidelines. While related to infiltration performance ( $P_{inf}$ ), clogging is treated separately as it reflects the physical degradation of the filter substrate observed in the field, which can explain a decline in  $P_{inf}$ , and requires targeted maintenance.

The performance results of the four bioretention basins, ranging from 83.21% to 85.23%, indicate technically satisfactorily functioning. However, these results are all within the intermediate performance zone, which signals a moderate risk of progressive degradation. The maintenance recommendations proposed in this study are not based on theoretical assumptions but are directly derived from the interpretation of the measured performance levels specific to this case. The recommendation to conduct two technical inspections per year (spring and autumn) for the drainage systems and inlet/outlet structures is based on a logic adapted to the annual operating cycle of bioretention basins in a northern climate. Spring follows snowmelt, which may result in sediment accumulation, while autumn precedes the freeze-up period and provides an opportunity to assess the condition of the structures before winter. This inspection schedule is thus strategically timed at the most critical periods of the year, without being excessive. A single annual inspection would be insufficient to detect and address problems linked to the two primary stress seasons, whereas three or four inspections would impose a workload that may be unsustainable for technical teams without demonstrated added value. In this sense, the proposed frequency is both reasonable and targeted, while remaining operationally feasible, as it corresponds

to the level of risk inferred from the measured results without overburdening human or financial resources. It is therefore a balanced measure, grounded in the observed facts of the case study and the expected functioning of the infrastructure under real operational conditions.

Furthermore, the 75% threshold, which is assigned to bioretention basins that rely on full infiltration, is established as a critical level of technical performance. It serves as an operational alert point at which inspection or maintenance intervention becomes necessary. In this study, performance below 75% is considered critical, as it likely indicates a significant decline in system effectiveness, particularly in infiltration capacity and flow regulation. This threshold is not derived from a formal standard but is established as an operational reference based on the expected performance objectives and hydraulic risks identified in the local context. As such, it acts as a buffer zone, preventing rapid and costly deterioration if these issues are left unaddressed.

In the specific context of Avenue Papineau in Montréal, this threshold is particularly justified by the constraints associated with northern climates: repeated freeze–thaw cycles, heavy winter inputs of salt and sand, and the vulnerability of vegetation to harsh conditions all contribute to accelerated degradation of infiltration and retention performance. Furthermore, the bioretention basins are in a densely built-up area and are connected to a combined sewer network, which increases the importance of maintaining high performance levels to limit overflows during storm events. In this context, the 75% threshold allows for preventive intervention before the infiltration and regulation functions are significantly compromised.

However, this threshold should not be interpreted as a universal standard. In regions with more temperate climates, where freezing is not an issue, or for systems equipped with efficient subsurface drainage, a lower threshold (e.g., 65%) might be acceptable without compromising overall functionality. Conversely, in highly constrained environments or for aging infrastructure, a higher threshold (e.g., 80%) may be justified to maintain consistent service levels. More broadly, the adjustment of thresholds should follow local conditions and priorities: in tropical climates, water quality objectives may justify stricter criteria; in semi-arid regions, thresholds may emphasize infiltration and groundwater recharge; while in municipalities with limited technical resources, thresholds should balance performance objectives with operational feasibility. This flexibility ensures that the 75% reference adopted here remains a pragmatic guideline, while providing a transferable framework for adapting maintenance strategies across diverse regions.

## 5. DISCUSSION

The results obtained in this research reveal a significant performance of the bioretention basins analyzed on Papineau Avenue in Montréal, with values ranging from 83.21% to 85.23%. These performances far exceed the minimum level of 75% and are in the upper range of results reported in the scientific literature, requiring a medium priority for intervention. In comparison, Ahiablame et al. (2012) documented the variable effectiveness of bioretention basins, with a reduction in runoff volume and peak flow ranging from 40% to 97%, revealing a wide dispersion in performance depending on the context. Similarly, work by Davis (2008) and Hunt et al. (2008) showed median peak flow attenuations of 52% and 99.6% in basins located in Maryland and North Carolina, USA, respectively. More locally, Bond (2020) measured a retention performance of 84% in Montréal, which is very close to that observed in the present research. Le Cauchois et al. (2025) evaluated the effectiveness of bioretention cells and observed, for modeled events, peak flow reductions ranging from 30 to 34.5% and runoff volume reductions between 30 and 39%. For their part, Autixier et al. (2014) reported a reduction in runoff volume ranging from 13 to 62%, while Géhéniau et al. (2014) highlighted an average retention rate of 59.7% during warm seasons.

Figure 2 illustrates the systemic conceptual diagram used in this study. It provides an overview of the main components of the system (e.g., contaminants, storage/retention, infiltration, clogging, vegetation) and highlights the qualitative interactions among them. The diagram plays a structuring role by clarifying how the different factors considered in the methodology are interrelated and integrated into a coherent decision-making framework. As such, the figure serves as a conceptual reference that supports the reproducibility of the proposed approach and its potential application in other stormwater infrastructure management contexts.

It should be noted that Figure 2 is not an operational flowchart describing sequential steps or direct prioritization of interventions. Instead, the prioritization is derived later from the quantitative indicators and thresholds (Equations 1–5; Tables 1–5).

What sets this study apart, beyond the quality of the performances assessed, is the methodological approach adopted. The use of a systemic approach made it possible not only to assess technical performance but also to break down each infrastructure into critical sub-components (storage capacity, infiltration, vegetation condition, contamination, etc.). In this study, contamination was incorporated not as a separate quantitative indicator but through field observations of sediment deposition, organic debris, and road salt accumulation, which directly affect infiltration and vegetation health and are therefore considered systemic drivers of performance decline. This modeling of

interactions enabled a fine, integrated, and operational assessment of the basin conditions, rarely addressed in existing literature.

It should also be noted that the low dispersion of performance between basins (less than 2% difference) suggests a degree of homogeneity in the design and operation of the infrastructures, reinforcing the credibility of the results obtained. With this method, municipal managers now have at their disposal a structuring diagnostic tool that enables them to adopt a preventive maintenance logic based on risks and data. This paradigm shift, from reactive to proactive management, is an essential lever for ensuring the sustainability of infrastructures in an increasingly complex urban context, which is marked by intensifying urbanization and climate change impacts. To situate these results within the realities of Papineau Avenue, we explicitly considered the dual pressures of urbanization and climate change. In this study, urbanization was addressed through the physical and hydraulic context of the Papineau Avenue reconstruction project, located within a densely built corridor connected to the Curotte–Papineau combined sewer basin. The project was initiated to alleviate hydraulic overload caused by rapid urban densification, which increased impervious surfaces and runoff volumes, leading to frequent sewer overflows during intense rainfall events. The bioretention basin analyzed in this study was designed as part of this strategy to mitigate the direct impacts of urbanization by promoting local infiltration, reducing peak flows, and temporarily retaining runoff before its entry into the sewer network.

Climate change was considered through operational constraints specific to northern environments, where more frequent and intense rainfall events and repeated freeze–thaw cycles directly affect infiltration performance and substrate permeability. Field monitoring conducted between 2018 and 2020 highlighted the influence of these climatic stressors on basin behavior, particularly during spring thaw and high-intensity storms. Consequently, maintaining effective infiltration and drainage capacity under these evolving climatic conditions requires continuous observation and periodic maintenance to preserve long-term functionality and resilience. The findings of this comparative analysis and the solid results obtained at local level, reinforce the relevance of the systemic approach adopted. In addition to validating the effectiveness of bioretention infrastructures, this research proposes a structured approach to the preventive and sustainable management of stormwater infrastructures.

Finally, analysis of measured technical performance has enabled us to position the basins studied into distinct functional zones, enabling us to adopt a graduated maintenance plan based on their actual condition. Basins with a performance level over 90% are in optimum condition, showing no signs of functional deterioration. For these structures, a monthly visual inspection is sufficient to detect any potential anomalies at an early stage, in line

with the recommendations of the USEPA (2016; 2021) and Erickson et al. (2010). Conversely, basins whose performance is between 76% and 89%, as observed in all the bioretention basins evaluated in this study, fall into the “functional with signs of wear” category. In this case, a bi-annual inspection of the inlet and outlet devices, drainage elements and substrate is recommended to prevent debris build-up and maintain the permeability of the structures. Performance below the critical threshold of 75% is deemed inadequate, warranting a full technical inspection and immediate repairs. This performance level may compromise stormwater management objectives, particularly during heavy rainfall or potential overflows. Finally, specific measures are planned to address localized degradation identified during inspections, such as partial or total clogging by sediment or vegetation, requiring thorough cleaning, or loss of infiltration capacity due to substrate clogging, justifying replacement or regeneration of the filtering soil. These actions are prioritized according to their urgency and hydraulic impact and are part of a proactive maintenance approach based on empirical thresholds widely validated in the literature.

## **6. CONCLUSION**

This study demonstrates the relevance of the systemic approach to the development of a maintenance plan adapted to urban stormwater management infrastructures. By dissecting bioretention basins into functional components and analyzing their performance using specific criteria, it was possible to propose differentiated maintenance strategies based on the level of performance observed.

The results of the case study revealed variability in the performance levels of the basins assessed, highlighting the importance of rigorous, personalized monitoring for each infrastructure. The use of the systemic approach not only enabled us to gain a better understanding of the overall behavior of the structures from a technical perspective but also to plan targeted preventive interventions, promoting the sustainability and efficiency of the systems.

As such, this methodology can be a valuable tool for municipal managers in their decision-making by integrating the complexity of interactions between different infrastructure components. It offers an adaptable, reproducible, and scalable framework for the sustainable management of structures within the context of urban resilience.

For future work, it would be appropriate to extend the maintenance plan to other types of stormwater management infrastructures (retention basins, infiltration trenches, green roofs, etc.) and enrich the analysis with long-term data incorporating climatic, socio-economic, and environmental factors.

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