# BGI Performance Variability – Developing an Experimental Method

## Variabilité de la Performance des TBV – Développement d'une Méthode Expérimentale

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## RÉSUMÉ

Trame verte et bleue (TBV) présentent une variabilité de performance intrinsèque plus importante que les infrastructures traditionnelles de gestion des eaux pluviales (par exemple, les réseaux d'égouts pluviaux) en raison de facteurs environnementaux tels que la santé des végétaux, la structure du sol et la température, sous des régimes pluviométriques identiques. Toutefois, cette variabilité n'est pas explicitement exprimée lors de la communication de la performance attendue d'une TBV au sein de la communauté d'ingénierie ou de la communauté élargie des utilisateurs. Ces travaux visent à quantifier le « flou » de la performance des TBV par le biais d'une série d'expériences en laboratoire qui isolent les variables environnementales, afin de déterminer où se situe la plus grande variabilité au sein de l'TBV et de fournir une approche fondée sur les données pour la communication publique concernant les avantages et les risques des TBV. Les résultats préliminaires montrent qu'il existe une variation dans la réponse de l'TBV à un événement de même ampleur, intensité et durée, avec la même période d'assèchement antécédente, en raison de la variabilité de construction (variations entre les colonnes pour chaque répétition d'essai) et de la variabilité expérimentale (variations au sein d'une même colonne pour l'ensemble des répétitions d'essai). Cette variabilité a été observée en quantifiant les différences dans la profondeur de mise en charge, la profondeur de débordement et le volume percolé. Ces résultats soulignent l'importance de déterminer davantage la variabilité des IBV dans des conditions variables afin d'améliorer la compréhension de leur performance et de développer une méthodologie permettant de quantifier plus précisément cette variabilité.

## ABSTRACT

Blue-green infrastructure (BGI) systems have more inherent variability of performance than traditional stormwater infrastructure (e.g., storm sewers) due to environmental factors, such as plant health, soil structure, and temperature, under the same rainfall patterns. However, this variability is not expressed when expressing the expected performance of a BGI within the engineering community, or the larger community of users. This work seeks to quantify the “fuzziness” of BGI performance through a series of laboratory experiments that isolate environmental variables, such that it is understood where in the BGI the greatest variability may occur as well as provide a data-driven approach to public communication on the benefits and risks of BGI. Preliminary results show that there is variation in the BGI’s response to an event of the same size, intensity and duration with the same antecedent dry time due to construction variability (variations between the columns for each trial repetition) and experimental variability (variations between the same column for all trial repetitions). This variability was observed through quantifying the differences in the ponding depth, overflow depth, and percolated volume. These findings signify the importance of further determining the variability of BGIs under varying conditions to enhance understanding of BGI performance and to develop a methodology for further quantifying this variability.

## KEYWORDS

Blue-green infrastructure, environmental conditions, measurement error, performance, variability

# 1 INTRODUCTION

With the movement to blue-green infrastructure (BGI) as a method to manage stormwater, stormwater solutions are moving from historically underground and out of the public view, to the street-level and open to the public. While BGI utility has been demonstrated and is known within the stormwater community, there is often criticisms by the public of these systems BGIs (Meenar et al. 2020). A common public critique is that they do not prevent flooding nor protect safety from flooding, however this stems from a lack of understanding of the expected function of what BGI can and cannot do (Bezak et al. 2024; Li et al 2022). Naturalized systems, like BGI, have multifactored benefits over grey infrastructure (such as resiliency, carbon sequestration, heat island mitigation, etc.; Cook et al. 2024; Scheiber et al. 2024). These systems have more inherent variability of performance than traditional stormwater infrastructure (e.g., storm sewers) due to environmental factors, such as plant health, soil structure, and temperature, under the same rainfall patterns (e.g., Amur et al. 2022).

The central hypothesis driving this research is that given the same inflow hydrograph to a BGI, isolated environmental variables will result in significant variability of the outflow hydrograph. With this understanding of the potential range of outcomes for a BGI can help stormwater professionals to better connect BGI choice and design to a specific need, and to provide more understanding to communicate with the project. In these initial stages of the project, the goal is to develop a method for stormwater professionals to better quantify the expected variability of BGI under a range of environmental conditions, including antecedent dry time, vegetation growth, and seasonality. The results from this initial study will then be able to demonstrate BGI performance variability with a range of possible hydrograph shapes (e.g., Fig. 1), that is their “fuzziness.”

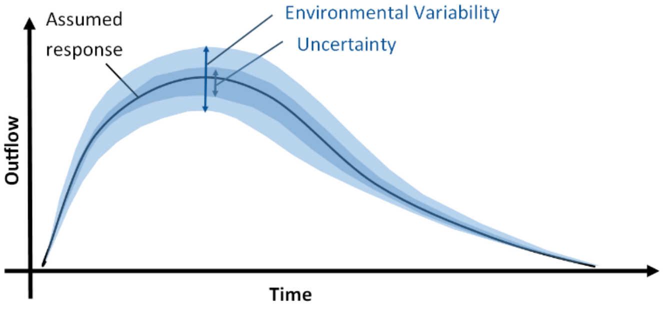

Figure 1. Conceptual example of hydrograph ‘fuzziness’

# 2 METHODS

It is expected that there will be variability in BGI performance due to environmental variables, but first we must also consider the source of the data that is measuring BGI performance. BGI performance is often quantified with field-based sensors, and the sensing instruments themselves can have error or the observations within a BGI can be below the sensors’ accuracy (e.g., too small ponding depths). Another factor of variability can come from input uncertainty, such as variable rainfall patterns. Measurement accuracy and input uncertainty have been previously studied and there are ways to incorporate that variability into understanding BGI performance. Output uncertainty, how water leaves BGIs, has been reported but not aggregated in a way that is useful for stormwater professionals to use in design or articulate risk.

To understand BGI performance variability due to environmental conditions, first the method that will be used to test this must undergo examination to quantify the variability due to experimental design.

## 2.1 Experimental Design

Three laboratory bench-scale soil columns (replicates) are used to isolate the effect of antecedent moisture conditions. There are three columns that are 54 cm in height (38 cm of soil and 15 cm of ponding) and 15 cm in diameter (Fig. 2). Inflow is delivered to the columns via a custom-made apparatus and are tested for consistent delivery of water (at a 5:1 ratio BGI surface area to drainage area) to the soil columns such that inflow instrumentation error can be quantified. Percolation is controlled via a peristaltic pump that sets the outflow rate to mimic typical in situ percolation rates. Three key performance parameters are measured: ponding depth and overflow (ultrasonic sensor, 100 mm-2.7 m target range, resolution: 0.25 mm, accuracy: +/- 0.1 of target range), percolation (tipping bucket rain gage, +/- 1% for 0 to 30 mm/hr and +/- 5% for 30 to 120 mm/hr).

Figure 2. Experimental setup with three soil column replicates, inflow delivery system, and outflow measurement.

## 2.2 Trials

In the first trial, the peristaltic pump was used to simulate a percolation rate of 1.5 mL/min. The columns were constructed as identical as possible with care taken to match soil volumes, heights, compaction, and ponding depth. The columns were filled with loamy sand soil (i.e., 84% sand, 15% silt, and 1% clay by USDA soil classification). A simulated event of 45.7 mm of rainfall and a 3-hour duration (constant intensity of 15.2 mm/hour) was applied to each replicate seven times. The antecedent dry time between events for the first trial was kept consistent at 2 days between events. In the second through fourth trials, the aforementioned experimental parameters were the same (same event size/duration/intensity and same percolation rate) apart from the antecedent dry time, which was increased in a range from 3-5 days between events. In the fifth and sixth trials, the same event size, duration and intensity were tested under a new percolation rate (5.2 mL/min) and varying antecedent dry conditions (for instance, the fifth trial would have an antecedent dry time of 2 days, and the sixth trial would have an antecedent dry time of 3 days).

# 3 PRELIMINARY RESULTS

Results from the first trial show that generally, the soil column replicate response is similar, with slight variability due to the construction of the columns and general experimental variability between trials. The experimental variability was defined as the variability for one individual column for each of the seven trials (e.g. comparing all trial results for only column A). The construction variability was defined by the differences between all three columns (A, B, C) for each individual trial repetition (e.g. comparing column A, B, C for only trial 1). Despite the three columns being designed as identical as possible, the construction variability was found to have a larger impact than experimental variability, which highlights a crucial aspect of real-world BGI design and construction. Despite all the careful considerations when designing BGI, the same systems constructed with "identical as possible" specifications will still demonstrate differences in performance and responses to the same event due to slight variations in compaction, infiltration rates, ponding zone, etc., which contribute to the overall variability.

Fig. 3 depicts the variations in the ponding depth due to the construction and experimental variability in terms of ponding depth. The “fuzziness” of the graph was constructed using confidence intervals of 95%. As demonstrated in Fig. 3, there is minimal variability while the depth increases with the addition of the simulated inflow, and the significant differences arise after the peak ponding depth is achieved.

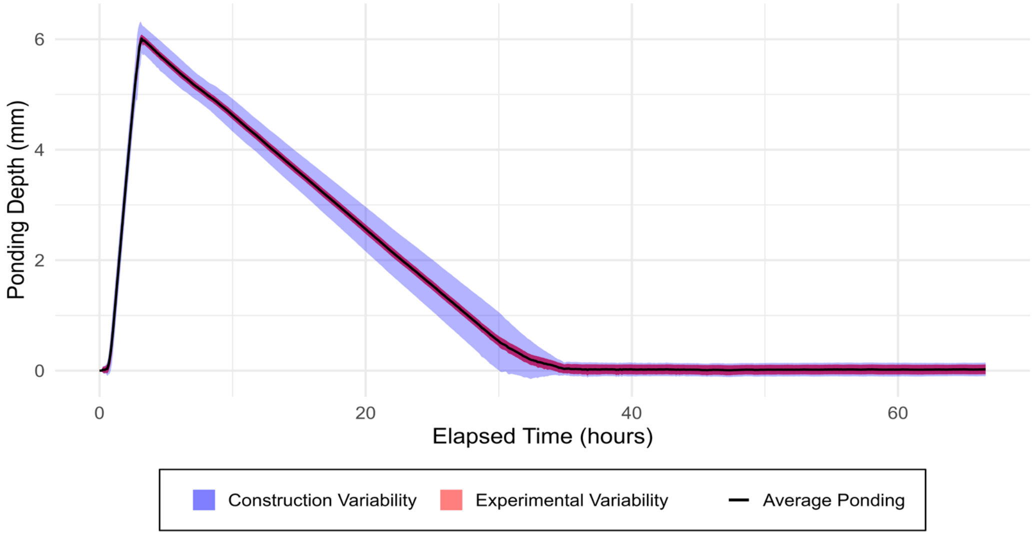

Figure 3. Ponding depth variability plot for constant intensity 15.24 mm/hr, 3-hour duration event.

Furthermore, the variations have also been observed regarding the overflow parameter. The first simulated event resulted in peak ponding depths that were significantly close to the overflow point of the system. One column, B, slightly but consistently overflowed for each of the seven trial repetitions to an average peak overflow depth of 0.45 mm. Column A was found to overflow for two of the trial repetitions, to an average peak overflow depth of 0.19 mm. Lastly, column C was not observed to overflow for any of the seven repetitions. These findings further highlight the importance of examining and quantifying this variability, as three identical as possible columns have slightly different responses to the same event. For constructed BGI systems, this concept becomes increasingly important as the variations, while small at first, could influence overall event responses (presence of overflow).

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