Response of green roof performance to multiple hydrologic and design variables: a laboratory investigation

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ABSTRACT

Multiple factors affect green roof performance and their effects might vary at different stages of operation. This paper aimed to link green roof performance to hydrologic variables (antecedent moisture condition (AMC) and rainfall intensity) and design variables (growing medium (GM) type and depth) under multiple dimensions at the early stage of operation using laboratory experiment data. The results showed that the AMC is the most influential factor of hydrologic performance, whereas the GM type appeared to primarily affect the nutrient levels of the outflow. The significant main effects of other variables and interaction effects between two variables point to challenges in green roof design.

Key words | design variables, green roof, hydrologic performance, hydrologic variables, nutrient leaching, water quality performance

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INTRODUCTION

Urbanization not only sharpens stormwater runoff hydrographs but also degrades stormwater runoff quality. For attenuating or eliminating the effects of urbanization, green roofs are considered a practical low-impact development (LID) technology alternative to conventional stormwater management technologies. Many studies (e.g., Beecham & Razzaghmanesh 2015; Carpenter *et al.* 2016) have assessed and confirmed the dual benefits of green roofs. The reported degree of benefits, however, appears to vary among studies, which might be ascribed to the variations in climatologic conditions, physical and chemical characteristics of the growing medium (GM), green roof configuration, or a combination of these factors.

In the application of green roofs, the extensive green roof (referred as 'green roof' throughout this paper) is popular as it is applicable to existing buildings. As for green roof hydrologic performance, a review study by Li & Babcock (2014) reported that the retention rate (RR) of green roofs is in the range of 30–86%. The existing body of knowledge suggests that the GM type and depth (Dunnett *et al.* 2008; Yio *et al.* 2013), antecedent dry weather period (ADWP) or antecedent moisture condition (AMC) (Razzaghmanesh & Beecham 2014) and rainfall characteristics (Villarreal & Bengtsson 2005) can affect green roof hydrologic performance. From the perspective of water quality, green roofs can act as a source or sink of pollutants. The GM of green roofs is often enriched with nutrients owing to the use of compost or fertilizer to sustain vegetation growth and is therefore a common source of nutrients (Bliss *et al.* 2009), especially in the early stage of their operation. Green roofs, however, would turn into pollutant sinks after exchangeable pollutants are exhausted (Alsup *et al.* 2011). Therefore, whether a green roof behaves as a source or sink of pollutants could be a function of the GM, age and configuration, apart from the vegetation and the use of fertilizer (Emilsson *et al.* 2012). In addition, the water quality performance of a green roof might be also associated with the hydrologic performance.

doi: 10.2166/wst.2018.275

To date, a very limited number of studies have been undertaken to link GM characteristics to green roof performance. Furthermore, the literature has revealed that green roof performance is affected by multiple variables (both hydrologic and design variables). In addition, previous works have also demonstrated the effects of some variables, including rain intensity and substrate depth, on green roof hydrologic performance using the US EPA's Stormwater Management Model (Alfredo *et al.* 2010) and conceptual and mechanistic models (Palla *et al.* 2012). The ADWP, which is associated with the antecedent moisture, was demonstrated to be the important initial condition for successfully modeling hydrologic performance of green roofs in the conceptual model employed by Palla *et al.* (2012). Therefore to better understand green roof performance and thus optimize its design, examination of the effects of hydrologic and design variables under multiple varying conditions is required. On the other hand, although green roofs have the potential to remove various pollutants, this aspect differs from other LIDs because they receive inflow as precipitation, which has better water quality compared to urban stormwater runoff. Pollutant leaching likely occurs at the initial stage, which can be problematic and should be investigated. Therefore this paper aimed to analyze the effects of hydrologic (AMC and rainfall intensity) and design variables (GM type and depth) on green roof performance in the early stage of its operation.

MATERIAL AND METHODS

Investigation under multiple varying conditions is very challenging, if not intractable, using pilot- and full-scale green roofs. Thus, laboratory experiments were conducted using green roof cells exposed to *multiple varying conditions* by varying design variables (GM type and depth) and hydrologic variables (rainfall intensity and AMC). Figure 1 shows the design diagram of the green roof cells. ZinCo filter sheet, drainage layer (FD 25-E drainage board with water retention cups upside down) and protection mat (SSM 45) were placed beneath the GM. Each cell had a surface area of 0.57 m × 0.41 m and a 1.5 cm diameter drainage hole. The cells were vegetated with sedum, which is locally available and easy to maintain. In addition, sedum is the most commonly adopted plant due to its tolerance to extreme temperature and high wind speed, and its limited water consumption requirements (VanWoert *et al.* 2005; Berretta *et al.* 2014). After planting, the cells were watered with the amount that satisfied water requirements but did not produce outflow from the cells, and placed under a photoperiod of 10–12 hours every day. The slope of the green roof cells was fixed at 1%. Three different types of GM were investigated, as they are locally available and/or used in the City of Calgary, Alberta, Canada: ZinCoblend-SI (GM I), Eagle Lake rooftop media blend (GM II), and SOPRAFLOR I (GM III), at three depths (100, 150, and 200 mm). The GM composition and several physical and chemical characteristics of each type of GM are given in Table 1. The GM field capacity was tested using ASTM standard test method (E2399). The particle size distribution was characterized by the sieve analysis method. The nutrient contents of the GMs were measured by the water extraction method (Hurley *et al.* 2017), which is a modified version of the field leach test of the US Geological Survey.

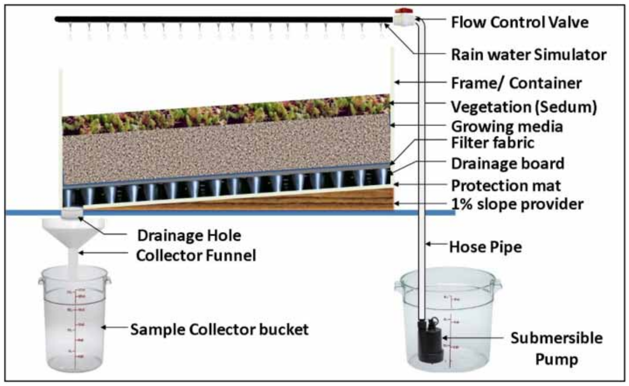

Figure 1 | Diagram of green roof laboratory cells.

In the experimental study, 2-, 5- and 10-year storms were simulated and applied to the cells in 1-hour durations. The duration of 1 hour has been often used to examine the operation of source control practices such as green roofs in the City of Calgary (The City of Calgary 2011). The rainfall intensities, which were uniform over the duration of the events and corresponded to 2-, 5-, and 10-year storms, were 14.09, 20.27, and 24.31 mm/hr, respectively. The storms were applied to the cells under three different AMCs: dry (<20%), normal (20–30%), and wet (>30%). The threshold values of the AMCs were determined based on average GM moisture measured on a 171 m^2 pilot-scale extensive green roof, which was constructed using GM I during 2015–2016 in the City of Calgary. Average GM moisture was calculated using measurements at five locations and two depths (top and 5 cm deep) for each green roof cell.

To investigate the effects of the four design and hydrologic variables at three levels, 81 experiments were conducted. In each experimental run, deionized water was used to generate the storm event, thus no additional pollutants were

Table 1 | Physical characteristics and nutrient contents of the three types of GM

Growing media type	GM I ZinCoblend-SI	GM II Eagle Lake rooftop media blend	GM III SOPRAFLOR I
Composition	High-quality recycled materials and minerals, enhanced with high-quality compost	Peat moss, fir bark fines, compost, sand, pumice and perlite	Pumice, sand, vegetable compost, perlite, and blond peat mixed with highly porous mineral aggregate
Average particle size D_{50} (mm)	3.75	0.85	1.75
Dry density (g/cm^3)	0.84	0.99	0.75
Field capacity (%)	38.28%	48.70%	41.92%
TN[a] (mg/kg)	239.40	819.00	259.80
TP[b] (mg/kg)	130.80	96.80	190.60

[a]TN: total nitrogen.
[b]TP: total phosphorus.

added to the cells. The hydrologic performance of green roofs has been assessed in terms of retention and detention. The most common metrics for depicting water retention capacity of green roofs is RR (Stovin *et al.* 2012; Nawaz *et al.* 2015; Stovin *et al.* 2017); while several detention metrics such as lag time (LT), peak flow reduction, and peak delay, etc. have often been used (Stovin *et al.* 2017). In this paper, the hydrologic performance of the cells was assessed using two hydrologic metrics: RR and LT. The RR is the percentage of rainfall captured by the green roof cells and the LT is the time interval between the onset of rainfall and the onset of outflow from the cells in an event. The water quality performance of the cells was evaluated using the event mean concentrations (EMCs) of several water quality parameters including nitrate, ammonia, total nitrogen (TN), orthophosphate, and total phosphorus (TP). A flow-weighted water sample was collected and assayed for nutrient EMCs in each experimental run.

Statistical analysis techniques were applied to examine the roles of these design and hydrologic variables on the performance of the cells. Multi-way analysis of variance (ANOVA) was conducted to investigate the main effects of individual explanatory variables and the interaction effects between two explanatory variables at the 5% significance level. Linear regression analysis was also adopted to quantify the dependence of the dependent variables (the performance evaluation metrics) on an explanatory variable.

RESULTS AND DISCUSSION

Effects of the design and hydrologic variables on the hydrologic performance

Multi-way ANOVA was conducted for both the RR and the LT and the results of the main effects and the contributions of the explanatory variables to the total variation are summarized in Table 2. As illustrated in the table, the main effects of all four explanatory variables on LT were found to be significant; and all the explanatory variables except the GM depth appeared to significantly affect the RR. As the AMC contributed the majority of the variations of both the RR and the LT (above 60%), the AMC is the most influential factor that governs the hydrologic performance among these explanatory variables. The GM type and rainfall intensity appeared to play secondary roles in the

Table 2 | The main effects of the design and hydrologic variables on the evaluation metrics of hydrologic and water quality performance

Variable	RR	LT	Nitrate	Ammonia	TN	Orthophosphate	TP
Growing media type	S (5.39%)	S (7.20%)	S (30.51%)	S (31.76%)	S (77.31%)	S (86.14%)	S (88.04%)
Growing media depth	NS	S (0.57%)	S (18.88%)	NS	S (1.09%)	NS	S (0.53%)
AMC	S (80.05%)	S (62.39%)	S (3.63%)	NS	S (6.82%)	S (1.86%)	S (1.83%)
Rainfall intensity	S (3.87%)	S (6.13%)	NS	NS	NS	S (3.51%)	S (3.42%)
Error	(3.46%)	(9.03%)	(7.53%)	(28.65%)	(4.23%)	(3.37%)	(2.17%)

S and NS denote significant and insignificant effect, respectively. The numbers in parentheses are the contributions of the variables to total variation.

hydrologic performance, as their main effects were significant but not as dominant as that of the AMC. The GM depth had little to no effect on the hydrologic performance due to the absence of its main effect on the RR and its negligible contribution compared to the contributions of other explanatory variables investigated on the LT.

The dependence of the RR and the LT on the AMC is further displayed in Figures 2 and 3, respectively, for all three GM types. Regardless of the potential effects of GM type, depth and rainfall intensity, the RR and the LT were strongly and negatively dependent on the AMC. The results further confirmed the dominant role of the AMC on the hydrologic performance of the green roof cells. In addition, the RR of GM I appeared to be more sensitive to the AMC than that of GM II and GM III, as the relatively large regression slope was calculated for GM I (Figure 2); whereas the LT of GM II and GM III was more sensitive to the AMC than that of GM I (Figure 3).

The identified significant interaction effects between two explanatory variables are provided in Table 3. For the RR, significant interaction effects between the AMC and GM type and between the GM type and rainfall intensity were observed; while significant interaction effects between the AMC and GM type and between the AMC and GM depth were found for the LT. As examples to illustrate the significant interaction effects, the interaction plots (Figure 4) between the GM type and the AMC, which display the variations of the mean hydrologic metrics among three AMC scenarios (dry, normal, and wet) given a GM type, are shown for the RR and the LT, respectively. The plots

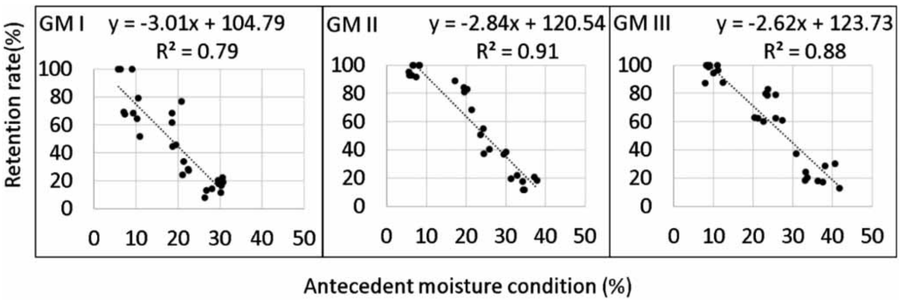

Figure 2 | Relationship between the AMC and the RR for the three different types of GM.

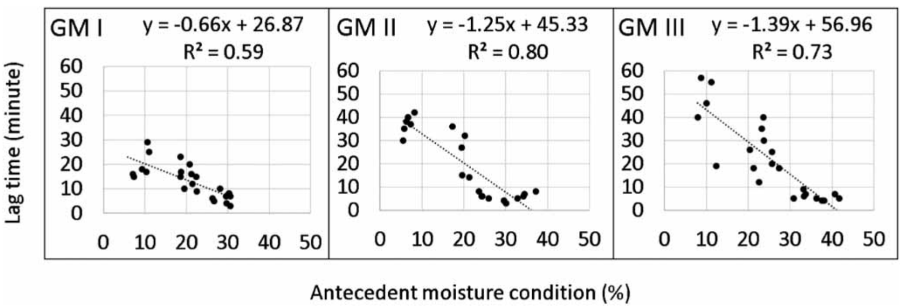

Figure 3 | Relationship between the AMC and the LT for the three different types of GM.

Table 3 | The identified interaction effects between two explanatory variables on the evaluation metrics of hydrologic and water quality performance

RR	LT	Nitrate	Ammonia	TN	Orthophosphate	TP
Type*AMC (1.02%)	Type*AMC (10.36%)	Type*Depth (30.98%)	Type*AMC (11.42%)	Type*AMC (4.34%)	Type*Depth (1.64%)	Type*Depth (1.29%)
Type*Intensity (1.87%)	Depth*AMC (2.54%)			AMC*Intensity (2.38%)	AMC*Intensity (1.17%)	AMC*Intensity (1.30%)

The numbers in parentheses are the contributions of the interactions to the total variation.

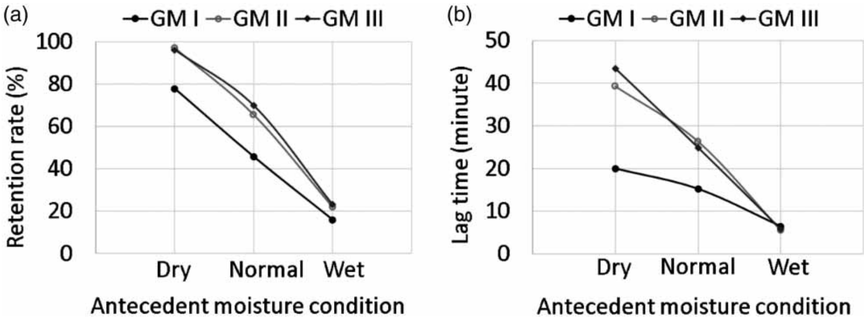

Figure 4 | Plots of interaction effects between the GM type and the AMC for (a) the RR and (b) the LT.

demonstrate that the main effects of the AMC on the RR and the LT are stronger in GM II and GM III than in GM I.

It is expected that RR tends to increase with a decrease in AMC. Razzaghmanesh & Beecham (2014) stated that a longer ADWP, which corresponds to a lower AMC, leads to a higher RR of green roofs as the GM would have more capacity to retain water in the next event. Similar results were also obtained in a study by Stovin *et al.* (2012), which showed an increase of RR with the increase of ADWP. All the results suggest that the AMC strongly affects green roof hydrologic performance but its affect would be quantitatively different in different GMs.

Among these three GM types, the RRs of GM II and GM III, which have higher field capacities compared to GM I (Table 1), were observed to be larger than those of GM I given same AMCs (Figure 2). In addition, GM I produced the shortest LT among the three GM types (Figure 3). The results are consistent with the finding by Bengtsson *et al.* (2005) that outflow from green roofs does not occur until the GM reaches its field capacity. Therefore, a high field capacity leads to a delay in outflow from green roofs, and consequently enhances the RR. However, when comparing GM II and GM III, GM III, which has the lower field capacity, appeared to further delay outflow. This result might imply that other physical characteristics, e.g. particle size, might also play a role.

The results demonstrate that among these investigated variables, the AMC played the most important role in hydrologic performance. This suggests the importance of monitoring AMC prior to a storm event. To fairly evaluate the hydrologic performance of green roofs, the role of the AMC should be taken into consideration, as the AMC can vary hugely among events and among different climatic conditions. From a modelling perspective, models capable of capturing the effect of the AMC are necessary for both event-based and continuous modelling. In addition to the AMC, the GM type is another important factor to be considered. The local availability of GM has often been the factor determining the GM used, thus caution should be taken when translating knowledge from other studies into practice locally.

Effects of the design and hydrologic variables on the water quality performance

Leaching of all investigated nutrients was observed in all the experimental runs. Therefore, nutrient leaching could be problematic at the early stage of green roofs. Multi-way ANOVA was conducted for the EMCs of the investigated nutrients and the results of the main effects and the contributions of the explanatory variables to the total variation are summarized in Table 2. In contrast to the hydrologic performance, in general the GM type appeared to play a dominant role in all investigated nutrient species, especially TN, orthophosphate, and TP. The variations in the EMCs of TN, orthophosphate, and TP were primarily explained by the GM type, whose contributions were in the range of 77% to 88%. Figure 5(a) illustrates the mean EMCs of nutrients for each GM type. GM II yielded the highest means of the EMCs of nitrate and TN and the lowest mean of the EMCs of ammonia. GM III produced the highest means of the EMCs of orthophosphate and TP. The differences among the EMCs of TN and TP can be explained by the nutrient contents of the GM (Table 1). In general, GM that is enriched with nitrogen or phosphorus yields higher EMCs of nitrogen or phosphorus in the outflow from the green roof cells. The GM depth and the AMC were also found to significantly affect the EMCs of three and four nutrient species, respectively. The significant main effect of rainfall intensity was only detected in the EMCs of orthophosphate and TP; and it appeared to be stronger compared to the effects of GM depth and AMC. These observations suggest different physical processes govern the leaching of nitrogen and phosphorus.

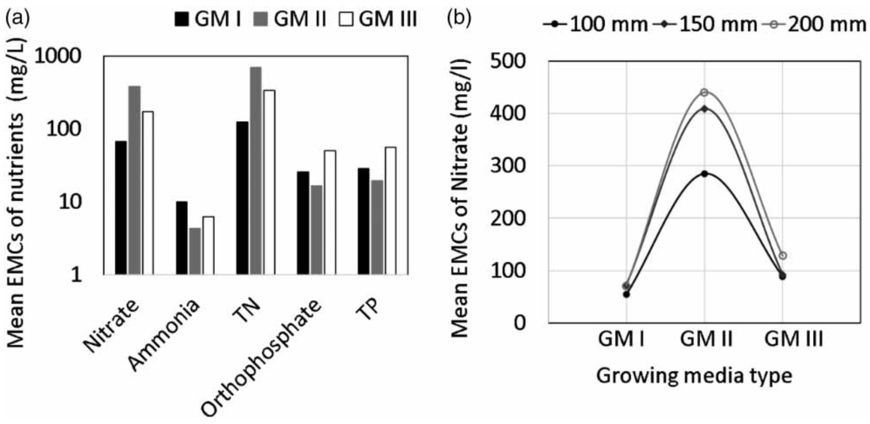

Figure 5 | (a) Mean EMCs of nutrients for the three GM types and (b) interaction plot of the GM type and GM depth for nitrate.

The dominant role of the GM type was detected on the EMCs of TN, orthophosphate, and TP; whereas the main effect of the GM type on the EMCs of nitrate and ammonia was not as strong as on other nutrient species, although it was statistically significant. As shown in Table 3, the interaction effects between the GM type and depth and between the GM type and the AMC were found to be significant and contributed a large percentage of the variations of the EMCs of nitrate and ammonia. In particular, the interaction effect between the GM type and depth contributed the highest percentage of the variation of the EMCs of nitrate. Note that the error items were in general below 9%; however, the error item was 28.7% in the EMCs of ammonia (Table 2). Thus, there is a large error in the analysis results for ammonia. The interaction plot between the GM type and depth for nitrate shown in Figure 5(b) demonstrates that the main effect of the GM type is stronger when the GM depth is more than 100 mm.

Overall, the GM type was identified to be the most important factor that governs nutrient leaching. Thus, when selecting or making a GM, the composition would be the key to reduce nutrient leaching. It might be an option to select a low-nutrient GM and gradually apply fertilizer according to the growth needs of the vegetation. On the other hand, the use of the dual-substrate layer consisting of an upper organic nutrition layer and a lower inorganic adsorption layer might also be a promising solution for mitigating/preventing nutrient leaching (Wang *et al.* 2017). In addition, variation in the effects of the hydrologic and design variables was observed among the investigated nutrient species. This poses a challenge in terms of controlling nutrient leaching, as different measurements might be required.

Note that the investigated results in this paper only represented the water quality performance of the green roof cells at their very early stage of operation. The water quality performance of green roofs is expected to be different between their early and mature stages because the roofs might act as a source of pollution in the early stage (as identified in this experimental study) but as a pollution sink in their mature stage. Further investigation into the duration of nutrient leaching in addition to the use of fertilizer and the role of vegetation is recommended. In addition, the exploration of effective ways to mitigate nutrient leaching (e.g., the use of soil amendments and the dual-substrate layer) is also suggested. On the other hand, the possibility of reusing green roofs' outflow should be studied considering the water quality levels at their different stages of operation. For instance, the nutrient enriched outflow of green roofs in their early stage of operation can be reclaimed for irrigation.

CONCLUSIONS

Among the investigated design and hydrologic variables, the AMC was identified to be the most influential variable affecting the hydrologic performance of green roofs. This implies that the inter-event meteorological condition would primarily determine the hydrologic performance. At the initial stage of green roofs, they would act as a source of pollution. In addition, nutrient leaching is largely affected by GM composition. The effects of other investigated variables were in general secondary or minor, but different contribution levels were observed among different nutrient species. These results suggest that both design and hydrologic variables should be taken into consideration when designing and optimizing green roofs. To predict green roof performance, a modelling tool should be capable of successfully capturing its variation resulting from the variations of these explanatory variables, especially the AMC and chemical contents of the GM, as well as the different performance at the different stages of operation. In particular, a modelling tool for quantifying pollutant leaching is needed to assess the possible negative impact of green roofs on stormwater.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Natural Sciences and Engineering Research Council of Canada (NSERC) and the City of Calgary for financial support, and the valuable contributions of the personnel of the City of Calgary, who were involved with the project.

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First received 13 November 2017; accepted in revised form 8 June 2018. Available online 18 June 2018