Research Article

A simple method for sizing modular green–blue roof systems for design storm peak discharge reduction

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Abstract
Typical green roof systems are used to improve downstream water quality and reduce long-term total runoff. However, they perform poorly at peak discharge reduction during large design storm events. This performance can be significantly improved by the addition of storage a layer (blue roof) underneath a green roof system. This paper presents a simple design methodology for designing modular green–blue roof systems to reduce this peak discharge. In particular, the methodology can be used for the preliminary design of the blue roof module's outflow control sizing. It is then shown how the resulting design can be incorporated into a standard hydrologic modeling system for a more detailed analysis. Results of an example design show that the addition of just 3.8 cm (1.5 in) of storage can result in a 38.6% reduction in peak discharge for a rainfall depth of 17.2 cm (6.78 in) compared to a green roof without underlying storage. Increasing the storage depth to 7.6 cm (3 in) for the same storm resulted in a 78.2% reduction of peak discharge.

Keywords Green roof · Green–blue roof · Stormwater modeling · Peak discharge · Low-impact development

1 Introduction

Green roof systems can contribute significantly to improving urban environments. Green roofs have been shown to reduce the urban heat island effect even at a micro-scale [1, 2]. These roof systems also provide rooftop insulation. For example, a study of green roof systems in Hong Kong showed internal building temperatures were reduced by up to 3.4 °C [3]. They can also play a role in pollution reduction. This can take the form of improved runoff water quality, CO_2 emissions, air quality, noise pollution, and even reduction in landfill volume from degraded building materials (see Rowe [4] for a review of pollutant benefits).

Despite these many benefits to the urban environment and ecosystem, there is still a reluctance on the part of many property developers to install green roof systems because of the associated costs. Therefore, a more direct economic argument is needed to increase the use of green roof systems. One potential economic benefit of green roof systems is the reduction in peak runoff from large rainfall events. If green roof systems could be designed to significantly reduce peak roof top discharge, they would reduce the need for downstream stormwater management infrastructure, which can be expensive and take up valuable land area. Unfortunately, most stormwater design manuals do not include design methodologies for quantifying design storm peak discharge reduction. Therefore, stormwater engineers are unable to realize these benefits and justify the installation of green roof systems.

In fact, Gashu and Gerbre-Egziabher [5] identified barriers to green infrastructure development and planning in Ethiopia, and a lack of understanding of peak discharge behavior could be said to contribute to at least three of these barriers, namely

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1. Technical barriers—without being able to quantify a green roof's impact at design storm depths, it is impossible to integrate any benefits into the overall stormwater system.
2. Regulatory barriers—without a firm technical understanding, regulatory approval and recognition to meet permit requirements will not be possible.
3. Capacity barriers (capacity barrier refers to a lack of resources)—without a definitive understanding of behavior and benefits, developers are less likely to invest in these technologies due to uncertainty and risk that they will not get an adequate return on their investments.

While Gashu and Gerbre-Egziabher's [5] work was focused in Ethiopia, these barriers are not unique to Ethiopia, especially the technical barriers.

Much research has examined green roofs' potential for reducing the peak and total discharge from a rooftop during rainfall events. Many studies have focused on longitudinal field studies of green roof installations with a goal of quantifying the rainfall—runoff behavior in terms of either a percent reduction or curve number. For example, Voyde et al. [6] reported a median peak flow reduction of 93% but noted that this reduction is dependent on a number of factors including rainfall depth, intensity, and antecedent conditions. The median rainfall depth in this research was less than 0.3 cm. Fassman Beck et al. [7] used green roof data from 21 different roofs and the Natural Resources Conservation Service (NRCS) Runoff Curve Number method to determine a curve number of 84 for "larger rainfall events." This work approach does not address the issue of the system's response to large design storm events due to the preponderance of smaller rainfall events in the data sets. Design storm depths used to design stormwater infrastructure vary depending on location and reoccurrence interval, but in non-arid locations they are generally at least 2.5 cm (1 in) for even 2-year 24-h storms and are over 10.2 cm (4 in) for 10-year 24-h storms in many locations. Table 1 contains the 2- and 4-year 24-h design storm depths for sample locations as references.

Theoretical routing models have been developed and applied to green roof systems to predict rainfall—runoff behavior [9], to calculate the system's initial abstraction [10], to quantify the detention performance [11], and to quantify their ability to reduce the peak discharge from major rainfall events [12]. However, in general it is seen that extensive green roof systems have limited storage capacity relative to large design storm events and, therefore, have minimal impact on peak discharge during these more significant rainfall events. In an experimental and modeling study of modular extensive green roof systems specifically looking at major rainfall events, Martin et al. [12] showed that the drawdown time for a typical modular green roof system is of the order of a few minutes. These results match what has been seen for non-modular green roofs as well [13]. This combined with an effective storage depth of a few centimeters, results in negligible reduction in peak discharge for these large design storm depths. While this may seem to contradict the much larger peak discharge reduction percentages found in other research, that is not the case as they are looking at the percent reduction of much smaller rainfall depths. For example, Jahanfer et al. [14] reported peak flow reductions of 58% for "large rainfall events" but large was only defined as depths greater than 10 mm (0.4 in). Kemp et al. [15] found vegetative canopies retained 2–17% of rainfall, but for a rainfall depth of only 9.3 mm (0.37 in). This pattern of analyzing smaller storms is very clearly shown by Stovin et al. [11] who created detention design charts that show approximations of both peak discharge reduction and runoff delay across a range of rainfall depths. For an extensive system, there is very high peak attenuation and delay for smaller storms, but it very rapidly decreases as the rainfall depth increases. In fact, the decrease is such that the maximum rainfall depth shown on the figures is 5.0 cm, which is half the 10-year 24-h design storm depth in many locations. While the reduction in peak discharge for smaller rain events is important hydrologically, for green roofs to impact the stormwater infrastructure design, it must have an impact at the design storm scale.

In addition to the detention of the green roof soil itself, there is also the ability to use other controls to impact the performance of green roofs. Fassman-Beck et al. [16] found that the horizontal flow path length to a roof drain impacted the effectiveness and suggested that this could be manipulated by design. Modular systems are even better suited to provide a similar delay as the outlets from the module itself can be used to restrict and delay flow in addition to the modules restricting the flow of water across the roof surface to roof drains, effectively lengthening the path to the drain.

Even with the potential for the modular green roof systems to be designed to enhance runoff detention, Martin et al. [12] found that the drawdown of the modules was very fast. One reason for the rapid drawdown time

Table 1 Rainfall depths for the 2-year and 10-year 24-h storms [8]

Location	2-year 24-h cm (in)	10-year 24-h cm (in)
Charleston, SC	10.7 (4.22)	16.4 (6.46)
Dallas, TX	10.2 (4.00)	15.2 (5.99)
Omaha, NE	7.54 (2.97)	10.9 (4.29)
San Francisco, CA	6.76 (2.66)	10.3 (4.06)

is the need for multiple drain holes in the base of green roof modules to avoid long-term pooling of water around the plant roots. A second constraint on green roof outflow controls highlighted by Martin et al. [12] is that the presence of soil in the module can lead to clogging of the drain holes if they are not sufficiently large. In their study, Martin et al. [12] sealed all but one drain hole in each submodule tested to increase the drawdown time though the effect was to increase it from the order of 10–20 s to a few minutes. To overcome the storage and discharge problems, so-called green–blue roofs have been developed and investigated [17, 18] that combine the water quality benefits of a green roof system and the detention benefits of a blue roof. A blue roof is simply an impervious roof system that includes rooftop runoff storage, so a blue roof is effectively a rooftop detention volume analogous to a detention pond. This has the advantage of adding detention volume to the rooftop of a building that would otherwise require underground storage or the allocation of land for a pond.

A green–blue roof is a blue roof located beneath a green roof system. See, for example, Shafique et al. [17] and Fig. 1. The performance of a green–blue roof system was evaluated by Shafique et al. [18] in a field study. The researchers measured rainfall and runoff and found that the peak discharge was reduced by 65% for a storm even with a maximum 60 mm/h rainfall intensity. This is consistent with prior field studies of green roofs that cite very high peak discharge reductions in the range of 50–80% [19]. These studies show that there is significant potential for using modular green–blue roof systems as part of a distributed low-impact development stormwater management system. However, their study focused on a particular blue–green roof system and, as such, does not provide a method for designing such a system for a particular land development. The current literature on green and green–blue roof systems does not include simple theoretical/analytic tools for developing flow routing models that can be used in design. Current reported results are specific to the module geometry tested and have no underlying model that would allow for the results to be generalized.

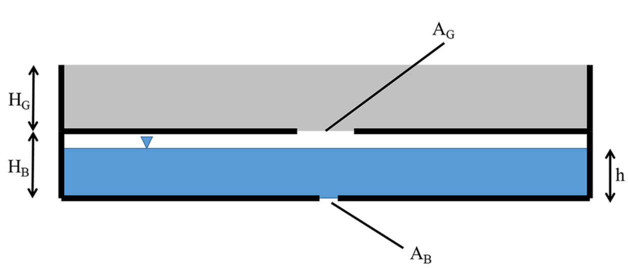

Fig. 1 Schematic diagram of a modular green–blue roof system. $A_G = \Sigma A_{Gi}$ and $A_B = \Sigma A_{Bi}$ are the cumulative drain areas of the green roof and blue roof, respectively. H_G and H_B are the heights of the green roof and blue roof modules, and h is the height of water at time *t* in the blue roof module

Green–blue roof systems have multiple benefits over standalone green or blue roofs. Because the green roof is not removed but simply raised above a storage layer, all the benefits of having a green roof described in the introduction would still be realized. Additionally, the blue roof storage layer below will provide significantly more storage, since it is not limited by the porosity of the soil. Further, the smaller orifice size possible in the storage layer (due to the lack of clogging risk from soil particles) significantly increases the detention time in a way which is not possible with soil-filled modules, though it is important to note that increased water detention on the rooftop would increase the live load during a rainfall event.

The goal of this paper is to present a simple flow routing model for modular green–blue roof systems that can be incorporated into event-based site hydrologic models. This, in turn, will allow engineers to realize the hydrologic benefits of modular green–blue roof systems in their stormwater infrastructure design. The model developed treats the modular green–blue roof as a small shallow storage volume (analogous to a detention pond or underground storage tank with gravity driven outflow) with calculated stage–storage and stage–discharge functions that can be determined from the module geometry and allows for the design of the outlet drains to optimize peak load reduction. The resulting simple design methodology can be used to size green–blue roof systems to optimize peak discharge reduction and realize the hydrologic benefits of these systems. This will, in turn, allow engineers to reduce the scale of downstream stormwater management infrastructure and make an economic case for green roof installation.

The design methodology presented is built on the recent experimental results of Martin et al. [12], which showed that for large storm depths, typical of design storm events, modular green roof systems saturate early in the storm and, therefore, offer minimal peak flow reduction. This finding, along with standard flow routing tools, forms the basis of the new simplified design methodology presented.

2 Green–blue roof design methodology

The green–blue roof system modeled is fundamentally a modular green roof system placed on top of an empty module (blue roof) that acts as a detention layer. See Fig. 1 for a schematic diagram of a green–blue roof system. The combined module has a plan area A_R with the upper green roof submodule having a depth H_G and total effective drain area A_G. The lower blue roof submodule has a depth

H_B and total effective drain area A_B. The total available storage for the system is

$$S = A_R(\phi H_G + H_B) + \forall_{\text{soil}} \quad (1)$$

where ϕ is the air-filled at field capacity porosity (detention storage) and $\forall_{soil}$ is the retention storage volume. It is assumed that the green roof total drain area A_G is large enough that it will not be clogged by soil particles and will not result in the plant roots sitting in saturated soil for prolonged periods.

For a green–blue roof to have the largest positive impact on a site's stormwater infrastructure, it needs to maximize both detention time and detention volume. This can be done by having significant storage capacity and small drain holes. However, the storage needs to be functional storage, that is, storage which will be reliably available. To ensure storage availability for design storms, stormwater regulations typically mandate a drawdown time over which the detention facility will return to its initial design state (empty in this case). Drawdown time regulations vary across jurisdictions though they are typically of the order of 2–3 days [20]. In a green–blue roof system, the retention storage becomes available over long periods, as water taken up by the plants and lost to evapotranspiration. This is a very slow process. For example, Voyde et al. [21] and Stovin et al. [10] found that evapotranspiration accounted for a maximum loss rate of only 2–3.5 mm/day in the green roof systems they studied. Therefore, $\forall_{\text{soil}}$ will be negligible compared to the detention storage available.

As shown in Martin et al. [12], the detention time for most modular green roof systems is of the order of a few minutes due to the constraints on the minimum size of drain holes and the reduction in effective storage due to the presence of the soil particles. Therefore, in the following calculations the green roof module is treated as a sub-basin with a time of concentration equal to the time step of the hydrologic model (typically 6–10 min). If the overlying green roof submodule has a longer detention time, then the model presented in Martin et al. [12] can be used to route the flow through the green roof submodule with the outflow exiting to the underlying blue roof detention volume.

Given the assumptions presented above, the routing model for the system has three steps. First, the rainfall hyetograph is routed through the upper green-roof submodule. The routing model treats the submodule as a basin with an area A_R and time of concentration $T_C = \Delta T$ where ΔT is the time step of the hydrologic model (also specified in some stormwater regulations, e.g., SC-DHEC 2002 [20]). The remaining parameter to specify the sub-basin is the initial abstraction. The initial abstraction could be calculated based on theoretical models [10]. However as discussed above, due to the drawdown restrictions, it can be assumed that there is very little retention volume available. Therefore, any initial abstraction would be very small and primarily limited to wetting of the plants on the surface. As such, for simplicity and to provide a conservative estimate of the peak discharge, the example below uses an RCN $= 98$, which is the same wetting loss that would be expected for an impervious surface. This routing model for the green roof is consistent with the experimental results of Martin et al. [12] that showed, for design events, the green roof module saturates and provided minimal peak flow attenuation. Therefore, for such extreme events, the green roof module performance is relatively insensitive to the soil properties as the soil is no longer able to retain water at the time of the peak rainfall intensity.

The outflow from the green roof submodule basin is then routed through the blue roof that is treated as a detention pond. The stage–storage relationship is given by

$$S = A_R h \quad (2)$$

where h is the depth of water in the submodule (stage). The stage–outflow relationship assumes an orifice flow and is, therefore, given by

$$Q = C_D A_B \sqrt{2gh} \quad (3)$$

where C_D is an appropriate discharge coefficient for the drain hole.

Finally, the outflow from the blue roof submodule (Q) needs to be routed over the underlying roof surface. This should be modeled like a standard roof system with an appropriate initial abstraction and time of concentration.

During a design rainfall event, the rain falls on the standard green roof module and will quickly flow through it. The outflow from the upper modules then enters the storage modules. While the rainfall rate (intensity multiplied by module area A_R) is greater than the discharge rate (Q) water will fill the storage module (blue roof submodule), and then, when the rainfall intensity decreases below the storage module discharge rate, the water level will begin to drop. If the blue roof submodule filled completely, the water would back up into the interface of the blue and green roofs and overflow the sides if the two modules were not sealed. If this occurs, the runoff from the green–blue roof system would be equal to the rainfall rate and the green–blue roof would be providing no detention or peak discharge reduction benefits. To avoid this, the outlet area in the storage modules should be sized such that the discharge rate when the storage module is full is equal to the inflow due to the peak rainfall intensity of the appropriate design storm. This ensures that the storage module never completely fills and is therefore always providing some detention and peak discharge reduction. If a green–blue roof system did have a sealed interface, then after the blue roof submodule filled the water would fill the green roof before overflowing the top of the entire system. This would improve the performance of the system, but since this would be dependent on the design of specific modular systems, the following modeling considers the case of an unsealed interface. Further, an unsealed design would make installation and maintenance easier.

A preliminary design methodology has been developed based on the routing model presented above and the design constraints of: (1) drawdown time and (2) preventing the blue roof submodule from completely filling. Because this was designed with primarily modular systems in mind, the methodology assumes that the depth is limited by a standardized manufacturing, but the orifice size can be customized by drilling or punching custom-sized holes. The design calculation steps are as follows:

1. Select a storage module depth (D) based on available products. The depth should be the largest available with a depth less than the depth of the appropriate design storm depth. The selected depth will also be constrained by the load capacity of the structure on which it will be placed though it is noted that the load due to water detention in the storage layer is only temporary. Therefore, the weight of the modules, soil and plant mater should be treated as dead loads, while the water would be considered a live load.
2. Establish the peak rainfall intensity $\left(i_p\right)$ for the appropriate design storm depth and rainfall hyetograph.
3. Calculate the peak inflow into the lower storage layer (assuming no attenuation in the flow rate due to flow through the upper green roof module) by multiplying the peak intensity by the storage module area

$$Q_p = i_p A_M \tag{4}$$

4. Calculate the effective orifice area $\left(C_D A_B\right)$ required such that the outflow rate through the orifice when the storage module is full is equal to the peak inflow rate $\left(Q_p\right)$. That is,

$$C_D A_B \sqrt{2gH_B} = Q_p \tag{5}$$

The effective orifice area $C_D A_o$ can be achieved with multiple outlets provided they sum to the same effective area. That is, provided

$$C_D A_o = \Sigma C_{Di} A_i \tag{6}$$

In this design procedure, it was assumed that there is no flow rate attenuation of the peak flow falling on the top of the green roof submodule due to flow through the module. This assumption allows the orifice to be sized without having to route the flow through the submodule. For a design depth storm, this will be of the order of a few minutes or approximately one time step in a standard hydrologic model. When a full hydrologic model for the site including the green roof system is developed, the flow through the submodule could be included.

This calculated effective orifice area will be a conservative value to ensure that that any blue roof module will not completely fill during the design storm. For shallow blue roof modules (relative to the rainfall depth), the storage capacity will be almost fully utilized, but for deeper blue roof modules (relative to the rainfall depth) there may be additional capacity that is unused. If there is additional unused capacity, it may be possible to reduce the effective orifice area such that more storage capacity is utilized without completely filling the module. This in turn will increase the peak flow reduction of the green–blue roof system.

However, it is recommended that some factor of safety maintained if the orifice area is reduced because once the blue roof module has completely filled any additional inflow would run out and the peak reduction benefits would be significantly impaired. This would give the green–blue roof a measure of resiliency for storms larger than the design storm depth and if clogging of the orifices occurs.

When deciding how many orifices this calculated outlet area should be split up into, there are a number of factors which must be considered. Multiple outlets are ideal since they provide redundancy in case any are ever clogged. However, multiple outlets mean each individual outlet is smaller and therefore more likely to clog. Based on the previous experimental work [12], orifices smaller than 1.6 mm (1/16″) are very prone to clogging though the precise minimum orifice size will be dependent on the soil gradation.

3 Design example

As an example, consider a green roof system consisting of a set of standard green roof modules of dimensions 30.5 cm × 61.0 cm × 10.2 cm (1 ft × 2 ft × 4 in) on top of a 30.5 cm × 61.0 cm × 3.8 cm (1 ft × 2 ft × 1.5 in) empty storage module that acts as the blue roof submodule. The system will be designed for a 25-year, 24-h storm in Clemson, SC. The total precipitation expected would be 17.2 cm (6.78 in), and, by using a Type II NRCS hyetograph, the maximum rainfall intensity is predicted to be 13.1 cm per hour (5.15 in per hour). Since this module is draining a 30.5 cm × 61.0 cm (1 ft × 2 ft) area, the peak inflow to the system will be 6.77 cm^3/s (2.39×10^{-4} cfs) as determined using (4). Then, assuming a flow rate equal to the peak inflow rate and a head of 3.8 cm (1.5 in) (the height of the module) (5) can be solved to determine the required effective orifice area $\left(C_D A_B\right)$. The effective orifice area required is 0.0797 cm^2 (0.0124 in^2), which would be a single orifice of diameter 0.31 cm (1/8″) or four orifices of diameter 0.16 cm (1/16 in). As a precaution, the storage model size could be increased from 30.5 cm × 61.0 cm (1 ft × 2 ft) to 61.0 cm × 61.0 cm (2 ft × 2 ft), with two green roof modules over each storage module. This would allow the use of two 0.31 cm (1/8 in) orifices.

To test the theoretical performance of this design, this green–blue roof system was modeled with a time step of 6 min (the required time step for calculations specified in SC-DHEC 72–307 [16]). The dual-layer design was implemented as described above for a large roof system with a plan area of 4,050 m^2 (1 acre) covered with the modules described above. Three separate models were developed and run. These models are:

(1) Impervious roof system covered with green roof modules with no underlying storage modeled as a basin with RCN = 98 and $T_C = 12$ min that accounts for the 6-min time of concentration for flow through the green roof module and 6 min for the time of concentration of the underlying roof.
(2) Impervious roof system covered with the green–blue roof system described above. This model used the outflow from case (1) and routed it through the blue roof submodule that was treated as a pond modeled using Eqs. (2) and (3).
(3) Impervious roof system covered with only the blue roof portion of the system described above. The rainfall was routed directly into the blue roof submodule that was treated as a pond modeled using Eqs. (2) and (3).

Model (2) accounted for the flow over the roof in the time of concentration for the green roof submodule. This is slightly out of order as the rainfall flows through the green roof module $\left(T_C = 6\,\text{min}\right)$ and then routes through the blue roof submodule before flowing over the impervious roof $\left(T_C = 6\,\text{min}\right)$. However, the modeling package does not allow for pond outflows to flow onto a basin forcing the approach described. The difference in the model discharge for model (2) from adopting this approach is likely to be minor compared to the overall model discharge.

Model (3) was included to show the relative impact of the green and blue roof components. However, it should be noted that a blue roof only system would be more susceptible to wind damage, being lifted off the roof due to lower weight [22].

Runoff hydrographs for hours 10–16 of the 24-h simulations are shown in Fig. 2. For the green roof system (1) the peak discharge was 0.208 m^3/s (7.35 cfs). However, the addition of the storage submodule, model (2), produced an 38.6% reduction in peak discharge off the roof compared to the green roof. This is a significant reduction in discharge for a 3.8-cm (1.5″) storage depth. Model (3), the blue roof without the green roof, performed very similarly to the green–blue roof. The peak discharge reduction was slightly lower and used slightly more storage. The results are summarized in Table 2.

During the rainfall event, the maximum water depth was 2.9 cm (1.2 in) for the green–blue roof (2). This was around 75% the depth of the blue roof submodule, 3.8 cm (1.5 in). If the orifice was reduced from 0.31 cm (1/8 in) to 0.24 cm (3/32), the blue roof submodule would just fill at the peak of the storm and the peak discharge reduction would decrease to 33.2%. So for this submodule depth, it would not make sense to adjust the orifice diameter.

As an example of the behavior of a module that had a larger depth, we can consider a fourth model (4)—the exact system as above, but with a 10.2-cm (4 in) deep blue roof submodule. The effective orifice area required for this system would be 0.0488 cm^2 (7.57×10^{-3} in^2), which would be a single orifice of diameter 0.24 cm (3/32″) or two orifices of diameter 0.16 cm (1/16 in). As can be seen in Table 2 [model (4)], the deeper blue roof submodule had a significant

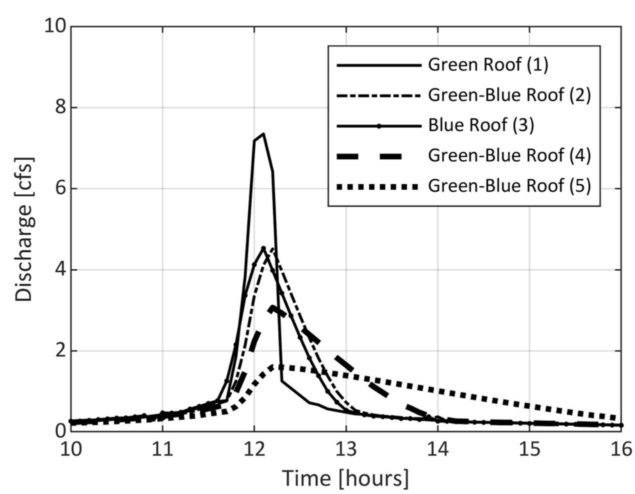

Fig. 2 Runoff hydrographs for the five simulations (Table 2) considered showing the dramatic reduction in peak discharge due to the presence of the blue roof submodule storage layer. The simulations are: (1) green roof, (2) green blue roof 3.8 cm deep with 0.31-cm-diameter orifice, (3) blue roof 3.8 cm deep with 0.31-cm-diameter orifice, (4) green–blue roof 10.2 cm deep with 0.24-cm-diameter orifice, and (5) green–blue roof 10.2 cm deep with 0.16-cm-diameter orifice

Table 2 Summary of the test cases modeled and their peak discharge, percent reduction, and maximum storage depth utilized

Simulation	Green roof (1)	Green–blue roof (2)	Blue roof (3)	Green–blue roof (4)	Green–blue roof (5)
Blue roof depth	–	3.8 cm (1.5 in)	3.8 cm (1.5 in)	10.2 cm* (4 in)	10.2 cm* (4 in)
Blue roof orifice diameter	–	0.31 cm (1/8 in)	0.31 cm (1/8 in)	0.24 cm (3/32 in)	0.16 cm (1/16 in)
Peak discharge	0.208 m^3/s (7.35 cfs)	0.128 m^3/s (4.51 cfs)	0.128 m^3/s (4.52 cfs)	0.087 m^3/s (3.07 cfs)	0.045 m^3/s (1.60 cfs)
Peak discharge reduction from (1)	–	38.6%	38.5%	58.2%	78.2%
Maximum storage depth	–	2.9 cm (1.2 in)	2.9 cm (1.2 in)	4.3 cm (1.7 in)	5.9 cm (2.3 in)

*Simulations (4) and (5) were originally modeled with a 10.2-cm (4 in) storage depth. However, as discussed in the text, because the maximum storage depth never exceeded 7.6 cm (3 in), these simulations would have the same performance for a blue roof depth of 7.6 cm (3 in)

impact with a peak discharge reduction of 58.2%. However, the maximum water depth was 4.3 cm (1.7 in), which is less than half of the submodule depth. Because the storage capacity utilization is low, the orifice area can be decreased.

Model (5) shows the results for the same module but with a single 0.16 cm (1/16 in) orifice. The peak discharge reduction is even higher at 78.2%, while the maximum water depth only reached 5.8 cm (2.3 in). At this point, the lower limit of orifice size has been reached (due to considerations of clogging as mentioned previously) and the only option to further improve performance would be to increase the area of the blue roof submodule to drain a larger area with the same orifice. However, if the submodule area was unable to be changed, it would be reasonable to use a shallower submodule, such as 7.6 cm (3 in), to reduce costs while not impacting the performance.

For all the examples discussed in this section, the drawdown time barely extended two modeling time steps (12 min) beyond the end of the rain event. While the blue roof does have a significant peak discharge rate reduction, the runoff is only delayed on the order of hours, rather than days. This is due to the orifices being sized to the peak of the rainfall distribution, so the detention primarily occurs during the peak rainfall intensity. The last few hours of a rain event have a much lower rainfall rate and less detention occurs because the orifices are oversized for this lower rate. While it is advisable to double check that the drawdown requirement is met, it should never be a controlling factor unless a blue roof has enough storage to capture the entire design storm (at which point the orifice would be sized only based on drawdown requirements), or in certain combinations of a very uniform distribution rainfall and larger storage depths.

4 Conclusions

This article presents a simple design methodology for sizing a modular green–blue roof system for peak discharge reduction during design storms. The methodology is based on recent experimental results that showed that green roof systems provide minimal discharge attenuation for high-intensity design storms, which is quite different behavior from what is observed in field studies, which are strongly biased toward smaller more frequent rainfall events. This experimental result allows for the use of a conservative flow routing model for modular green–blue roof systems and can be used to size the drain holes in the lower storage layer. The methodology can be used for preliminary design calculations that can be done prior to developing a full hydrologic model. Once the full model has been developed, it can be used to refine the design. Preliminary results indicate that the use of such system can lead to significant reductions in peak discharge from a roof compared to a standard impervious roof system. While the routing model presented is simple, the individual components, in particular the green roof module routing model, can be replaced with more sophisticated models (e.g., Stovin et al. [10] or Martin et al. [12]) after the preliminary design methodology has been followed.

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Availability of data and materials Some or all data or models that support the findings of this study are available from the corresponding author upon reasonable request.

Code availability Some or all codes that support the findings of this study are available from the corresponding author upon reasonable request.

Compliance with ethical standards

Conflicts of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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