Hydrologic performance of distributed LID stormwater infrastructure on land developments under a changing climate: Site scale performance improvements.

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Abstract

Traditional land development stormwater management replaces natural pervious surfaces with impervious surfaces such as pavements and buildings. This increases the rate of runoff that is typically then managed through drainage systems and controlled at or near the site discharge location. This approach often leads to increases in total runoff volume which can lead to higher peak flows in downstream stormwater systems. Low Impact Development (LID) technologies, such as porous pavements and green roof systems, provide an alternate approach to managing site runoff by mimicking the pervious surfaces they replace. However, these technologies are often used alongside traditional stormwater infrastructure as their entire hydrologic benefit has not been fully explored. Herein we examine the reduction in peak discharge and total runoff volume achieved through the use of porous pavements and green-blue roof systems (a green roof with an underlying storage volume) on three land developments located on the coastal plain of South Carolina (USA). Model results show that the inclusion of green-blue roof systems can significantly reduce peak discharge compared to traditional roof systems and common modular green roof systems, though they have negligible impact on the total volume discharged. Porous pavements significantly reduce total volume discharged, even when placed over low infiltration soils, but have less impact on peak flow depending on their design. The implementation of LID technologies has the potential to improve site performance beyond standard design rainfall depths indicating that the use of LID may offset the impact of climate change induced increases in extreme rainfall event depth and intensity.

Introduction

Ongoing new land development increases the impervious land area in communities across the country. This, in turn, increases the rate and volume of runoff from rainfall events. One study by the USDA (2007) estimated that in 2007 around 6,000 acres of open space was lost to land development each day. Water quality and flood mitigation regulations require that such land developments manage this increased runoff. Typically this requires that the runoff hydrograph, for certain specific design storm events, replicates some of the characteristics of the pre-development runoff hydrograph. For example, South Carolina state regulations (SCDHEC 2002) require that the peak discharge from a new development for 24 hour storms with return periods of both 2 and 10 years match the pre-development site peak discharge for the same design storms. Local municipal and county regulations may require other conditions to be met as well.

A common approach to meeting these regulatory standards is to collect and transport the runoff to the site outlet where the discharge is then controlled through various retention or detention facilities. See, for example Akan & Houghtalen (2003). However, this approach requires space for these retention or detention facilities or requires expensive underground storage volumes. Climate change also poses a risk when taking this approach. A warming atmosphere can hold more moisture. The additional energy will also increase the speed of the hydrologic cycle in some areas increasing the frequency and depth of extreme events (National Research Council of the National Academies 2011). Increased extreme event depths or shorter high intensity storms will lead to increased runoff from a land development's impervious surfaces and strain any detention or retention facilities. This can lead to flooding onsite or downstream of the site resulting in property damage and water hazards. Further, failure of such systems can lead to reduced water quality downstream with resulting public health problems (Gaffield et al. 2003).

An alternate approach to this problem is to use Low Impact Development (LID) or Best Management Practice (BMP) technologies in the design of stormwater management systems. Such technologies include porous pavements, green roof systems, infiltration trenches, and bioswales. There are advantages and disadvantages to each of these technologies. Water quality improvements from green roof systems have been studied (Morgan 2013) along with their long-term water reduction capabilities (Stovin et al. 2013). However, standard modular green roof systems exhibit minimal reduction in peak discharge of large design storms (Martin et al. 2020). Paved surfaces are significant sources of pollutants in stormwater (Lee et al. 2005, Li and Zuo 2013) due to sediment accumulation. Well-designed porous pavements reduce or eliminate surface runoff from paved surfaces as rainfall percolates through the pavement into the subbase. However, this in turn requires regular maintenance and flushing to prevent sediment from causing clogging (Scholz and Grabowiecki 2007). Such pavements are typically only viable for low-load pavements (Martin et al. 2018), and care must be taken to prevent sediment laden runoff from flowing onto these pavements.

Beyond sediment, porous pavement systems can have significant impact on water quality. For example Bean et al. (2007) reported field data that showed reductions in total nitrogen and total phosphorus (see also Gilbert & Clausen 2006 and UNHSC 2009). Heavy metal concentration reductions have also been reported. See for example Debo & Reese (2002), Van Setters et al.

(2006), Gilbert & Clausen (2006), and UNHSC (2009). The data on pollutant removal from green roof systems is less clear. A review by Rowe (2011) argued that green roof systems mitigate urban pollution through carbon capture, reduction in non-biodegradable roofing materials, and thermal pollution. However, due to the presence of soil in the green roof systems, there was a first flush increase in some pollutants though these reduced over time as the roof aged.

In general much of the emphasis in the use of LID and BMP is on improving water quality. As such, design guides typically focus on their design for trapping or retaining sediment. Design guides (Ellis et al. 2014, Field and Tafuri 2006, SCDHEC 2002) typically include qualitative information regarding layout and empirical or heuristic quantitative guides for sizing facilities. They generally do not include details on flow routing and, therefore, are of limited value when trying to establish the reduction in peak and total runoff that is gained through the use of LID and BMP. There are, however models for flow routing through some of these technologies. For example Schwartz (2010) presented a model for routing design storms through a porous pavement system to establish an effective curve number for the pavement. This technique was later generalized to produce guidelines for designing porous pavement systems to produce a specific effective curve number (Martin and Kaye 2014, Martin and Kaye 2016). A routing model for flow through a modular green roof system has also been proposed (Martin et al. 2020) along with design guidance for improving their capacity to reduce peak discharge from a rooftop through the use of a so-called green-blue roof. A blue roof is simply a rooftop detention volume and a green-blue roof is a green roof placed on top of a blue roof (Shafique et al. 2016a, Shafique et al. 2016b). This has the advantage of increasing the rooftop detention time and volume while still achieving the other benefits of a green roof.

The benefits of LID to individual land developments and larger scale watersheds have been examined in the literature. For example (Sun et al. 2014) simulated the reduction in runoff for individual rainfall events from a parking lot for a range of possible LID retrofits including porous pavements and infiltration trenches. Their results indicated that there was significant benefit for small depth storms but that the benefit was less pronounced for flood events. The study only considered a single parking lot and not an entire land development such that the interaction of the LID technologies hydrology with other site components, such as buildings and open areas, was not considered. Lucas (2010) examined the benefits of LID retrofits in an urban catchment and showed significant improvements in water quality and reductions in long term runoff. Avellaneda et al. (2017) examined the benefits of LID in a residential neighborhood and found significant reductions in discharge for rainfall events with return periods of up to 5 years. Rosseen et al. (2012) examined the water quality and hydrologic benefits of porous asphalt in a field study that captured one large storm. The pavement still reduced the peak flow suggesting that the storage layer of the pavement was able to capture and infiltrate the total rainfall up to and slightly beyond the peak rainfall intensity. There have also been multiple studies of catchment scale benefits of LID technologies. See for example Bedan et al. (2009) and Damodaram and Zechman (2013).

Studies that have examined site scale hydrology with multiple LID technologies include Zhu et al. (2019) who used field data to fit SWMM model parameters and then conducted a parametric study of the benefits. However, their field data only consisted of storm depths of 51 mm or less, well short of many water quantity design storm depths. Wilson et al. (2015) conducted a field study of conventional and LID site designs in North Carolina. The LID technologies were cisterns, grass swales, and bioretention. They observed a significant reduction in runoff volume. However, as with Zhu et al. (2019), the largest storm observed (79 mm) was less than a 24 hour two year return period storm for that location. Yang et al. (2020) calibrated a SWMM model and then simulated 15 years of performance and cost effectiveness of LID practices in Dresden, Germany. They found that results stabilized once continuous simulations were run beyond a year suggesting that, for a given storm simulation, the initial conditions can play a significant role. Luan et al. (2019) conducted a modeling study of Green Stormwater Infrastructure (GSI), another term for LID practices. They examined runoff reduction as a function of GSI implementation percentage for a 10 year 2 hours storm (depth of 137 mm). They found that porous pavements were most effective at reducing runoff volume while public green spaces were most effective at reducing peak discharge.

Qin et al. (2013) examined the benefits of grass swales, green roofs, and porous pavements in reducing urban flooding. Their modeling study examined a range of storm depths and rainfall hyetograph shapes. The authors varied the location of the peak rainfall intensity and found that swales performed best with earlier peaks in the hyetograph while porous pavements and green roofs performed better for middle and late peaks respectively. Hua et al. (2020) modeled the impact of a broad range of LID practices for short duration high intensity storms. A detailed life-cycle cost analysis indicated that bioretention, infiltration tranches, and rain barrels were the optimal solution for urban flood prevention for the location and storms considered.

There are numerous field and modeling studies of the hydrologic benefit of LID technologies at various scales from individual installations, site scale hydrology, and urban flood risk. In general the field studies, even long term studies, have very limited measurements for water quantity design level events. Modeling studies have considered such events for various combinations of LID practices. In modeling studies the LID technologies are designed for the local design conditions. However, global climate change models suggest that large storms will become more frequent and more intense (IPCC 2001 and Hutton et al. 2016). Therefore, it is important to understand how LID technologies designed for current conditions perform under a changing climate.

Another result from these modeling studies is that the performance of LID practices during a given storm is significantly influenced by the antecedent moisture conditions. There are two methods for capturing the antecedent conditions namely running a long term continuous simulation or making conservative assumptions regarding initial conditions for an event model. Storm water regulations typically include drawdown criteria that ensure that a system returns to its design state in a reasonable time period. For example in South Carolina the drawdown time is 72 hours (South Carolina Department of Health and Environmental Control 2002).

The goal of this study is to assess the impact of LID technologies at an individual land development scale at and above the water quantity design storm level. In particular, the study examines the reduction in peak discharge and total runoff when a traditional stormwater design is enhanced with the addition of modular green-blue roof systems and porous pavements. In all cases conservative estimates of the antecedent moisture conditions are made such that the results represent the worst case for the given LID design. The routing models used for the LID technologies are built on previously published experimental and modeling studies. These routing models are added to the site stormwater model and the overall site runoff is calculated for a broad range of 24 hour rainfall depths. The study examines three different land developments in the coastal plain of South Carolina. The sites modeled have fairly poor drainage soils that would normally preclude the use of porous pavements. However, porous pavements were still included with appropriately sized and located underdrains to take advantage of their retention/detention capacity. Finally, this study includes the use of a green-blue roof system that has not been examined in prior studies of site-scale LID technology.

The remainder of this paper is structured as follows. The three land developments modeled are described in the next section followed by a detailed description of the modeling approach used to design and implement the LID technologies into the site design. Results are then presented for the standard design and 3 distinct LID designs for each site. Both peak discharge and total runoff volumes are presented. The models are then run for storm depths in excess of current design storms to assess the potential of LID technologies to mitigate the increase in frequency and depth of extreme events due to a changing climate.

Case study site descriptions

The three different land developments modeled are actual developments from the coastal plain of South Carolina and include: a residential development (apartment complex), a mixed-use development, and a commercial site. For the location in the coastal plain that these sites were located, the 10-year 24-hour storm depth is 164 mm (6.47 in) and the 25-year 24-hour storm depth is 200 mm (7.89 in). In all cases the structures were taken to have flat roofs that could support modular green-blue roof systems. Table 1 contains basic properties of the sites including size and breakdown of land use. All sites were on type C and D soils and an infiltration rate of 1.3 mm/hr (0.05 in/hr) was used for modeling the underlying soils for the porous pavement (Akan and Houghtalen 2003). Porous pavement systems are not typically advised for types C and D soil due to their poor infiltration meaning that they fill up more rapidly and drawdown more slowly. However, as described below, including an underdrain that is placed to ensure adequate drawdown allows some of the retention and detention benefits of porous pavement systems to be realized even when placed over poor infiltration soils.

Due to some of the sites having more than one outfall and other topographic features, the larger sites could be broken down into smaller sub-sites. Because each of the sub-sites had a different breakdown of land use (roof, pavement, open, other impervious), the model results from the sub-sites provide a broader range of land use percentages to use in the analysis of the impact of LID on hydrologic performance. Therefore, the modeling results will be presented in terms of the six sub-sites rather than the three main sites. Table 2 contains the properties of the sub-sites that were considered.

Methods

The site designs and stormwater models for the standard layout were provided by the design firm that was working on these sites. The models were then modified to incorporate LID technologies, namely modular green-blue roofs and porous pavements. The sizing and modeling of the modular green-blue roof is based on the design approach proposed in Martin and Kaye (2020) which is a modification of current green roof modules for the purpose of increasing the peak flow attenuation and volume detention time. The porous pavement design is based on prior work (Schwartz 2010, Martin and Kaye 2014, Martin and Kaye 2016) for both full infiltration (undrained) and underdrained (drained) porous pavements.

The models for the standard design were provided by the design firm and had been created in Storm and Sanitary Analysis (SSA). SSA is the commercial site hydrology model in Civil 3D Site Design (https://www.autodesk.com/products/civil-3d/site-design) and is built on the EPA SWMM engine. To avoid any errors in porting these models into a different stormwater modeling system, the use of SSA was retained. The SSA models for the standard site development were modified to include the LID technologies. While SSA was used in this study, the models described herein can be implemented in any stormwater modeling software such that the approach does not limit users to a single software package.

The LID models were not calibrated against site data. However, they are built on standard hydrologic modeling methods described in the literature. See Schwartz (2010) and Martin & Kaye (2014) for porous pavement routing, Martin et al. (2015) for experimental results on sub-soil infiltration, Martin et al. (2020) for experimental details on the simplified green roof routing model appropriate for high intensity storms.

Green-blue roof design and modeling

The modular green-blue roof system uses 30 x 61 x 10 cm (1 x 2 ft x 4 in) plastic modules filled with expanded lightweight aggregate and vegetation on top of 61 x 61 x 10 cm (2 x 2 ft x 4 in) plastic modules which are empty. The upper modules are typical green roof modules. The addition of lower empty modules forms the blue roof portion of the green-blue roof system and provides significantly more storage volume for flow detention (see figure 1). The storage volume has a reduced orifice size compared to the outlet orifice in a standard green roof module. The smaller orifice slows discharge and detains the stormwater for a longer period of time. The orifices for the lower module are sized so the discharge from the module when it is full is equal to the maximum design rainfall rate for the site. This ensures that the module never overflows for storms less than the design storm. As a result, there is always a reduction in peak discharge. Herein evapotranspiration and water retention are ignored in the water balance. We make the conservative assumption that the soil is saturated at the start of the storm. This is the implied design state for green roof systems as the drawdown in soil moisture over a regulatory drawdown period is very small (order a few mm, see Stovin et al. 2013 and Voyde et al. 2010) compared to the design storm depth (order 150+ mm).

The design process for the green-blue roof is as follows. First, the area of the roof was measured from the CAD drawings to give the green-blue roof area (A). The peak inflow into the green-blue roof was calculated based on the peak rainfall intensity and is given by

$$Q_{peak} = i_{peak}A \tag{1}$$

where i_{peak} is the highest rainfall intensity during the 24 hour design storm. The total outlet orifice area was sized to ensure that this peak inflow could pass out of the green-blue roof without it overflowing. That is, the outflow through the orifice would be Q_{peak} at a depth less than or equal to the green-blue roof depth of $H = 20.4\ \mathrm{cm}$ (See figure 1) leading to

$$A_o = \frac{Q_{peak}}{C_D\sqrt{gH}}. \tag{2}$$

Finally, the roof perimeter was measured from the CAD drawings and this was used as the overflow weir length that has in invert at the top of the soil layer. While the system is designed not to overflow, the model was run for storm depths above the design storm depth so the weir was added to the model as a precaution. The outflow from the storage orifice and weir were then routed into the roof leaders. A flow diagram of this design procedure is shown in figure 2a. More details on the design process can be found in Martin & Kaye (2020).

The upper green roof modules are treated as a subbasin with a curve number of 98 and a time of concentration of 6 minutes. This time is a conservative estimate of the time it takes for rain falling on top of the module to flow through the soil, out of the upper module, and into the lower module. It is also the minimum time of concentration used in calculations. A weir outlet is also included at the height of the upper module to allow for discharge from the top of the module if it were ever to overflow. The lower module is represented as a storage node with the horizontal orifice size calculated as discussed above. Figure 2b shows the implementation of this model in SSA. The details of this model can be found in Martin & Kaye (2020).

Porous Pavement design and modeling

Porous pavements typically consist of a surface pavement (porous asphalt, pervious concrete, or permeable pavers) that have open connected void spaces which allow water to pass from the surface through to an aggregate subbase below. This aggregate subbase is an open graded stone which provides structural support for the pavement in addition to a storage volume for the stormwater. The subbase is situated directly on top of the underlying soil which allows the water stored in the subbase to slowly infiltrate into the soil over time. Most stormwater regulations require any stormwater storage on a site to return to an empty state within a certain period of time after a storm so that the capacity is restored for the next storm, the so called drawdown time. In South Carolina the drawdown time is 72 hours (SCDHEC 2002). If the soil infiltration capacity is sufficient to drain the entire storage volume in the required time, no underdrain is required. However, if the soil infiltration capacity is insufficient to completely drain the storage volume, one or more underdrains are required. Ideally it would be placed as high as possible in the subbase layer such that the volume below the underdrain would be capable of being drained via soil infiltration within the required time thus maximizing groundwater recharge and minimizing site runoff (Martin and Kaye 2014, Martin and Kaye 2016).

Porous pavement underdrains are sized similarly to the green roof module orifices. The underdrains' capacity when the pavement storage is full is designed to be equal to inflow due to the maximum design rainfall rate. This ensures that the pavement should never flood for storms up to the design depth. Due to the area of the pavements and the standard underdrain pipe sizes, "sizing" the underdrains for a pavement is really a matter of establishing how many underdrains are required for a pavement. Figure 3 shows the pavement depths and porosities (Φ) for the porous pavement design used in these models.

The design process for the porous pavement is as follows. First measure the pavement area and perimeter from the CAD drawings and calculate the peak inflow rate using (1). Then, the drawdown time is calculated using

$$T_D = \frac{\phi_p H_P + \phi_S H_S}{\phi_s f_s} \tag{3}$$

where ϕ_s and ϕ_p are the porosities (void fractions) of the subbase and pavement respectively H_s and H_p are the subbase and pavement depths in cm, and f_s is the saturated infiltration capacity of the soil in cm/hr. The ϕ_s in the denominator is to account for infiltration masking by the aggregate in the subbase (see Martin et al. 2015). If the drawdown time is greater than the required drawdown time (72 hours in this study) then an underdrain is required. The underdrain is placed so as to maximize infiltration. Therefore, the invert is located at a height (H_I) such that the water in the storage layer below can all be infiltrated over the drawdown period. This is given by

$$\phi_s H_I = 72 \phi_s f_s. \tag{4}$$

Finally, the size of the underdrain effective area required was calculated such that the pavement did not fully flood at the peak rainfall intensity for the design storm. This was calculated using (2) where H in this case is the vertical distance from the underdrain invert to the pavement surface. This area was then used to calculate the number of underdrain pipes required. For this study all underdrains were 10.2 cm (4 in) perforated pipes. A flow diagram of this method is shown in figure 4a.

In SSA, a porous pavement is modeled as a storage node with a subbasin area equal to the area of the pavement and with a curve number (CN) of 98 that accounts for surface wetting (Schwartz 2010). The storage node is given an elevation-storage curve which takes into account the porosity of each layer. That is, the storage area at any given height is the pavement area multiplied by the void fraction of the aggregate (see West et al. 2016 and Martin & Kaye 2014). The outlets for a porous pavement are a pump which represents the soil infiltration, a set of orifices that represent the underdrains, and a weir which would allow surface runoff if the pavement ever completely filled. The pump representing the exfiltration into the soil was set to "turn on" as soon as there was any water in the subbase and its discharge rate (Q_{pump}) given by

$$Q_{pump} = A\phi_s f_s. \qquad (5)$$

Multiplying by the subbase aggregate porosity (ϕ_s) accounts for the masking effect of the aggregate on the infiltration rate into the soil (Schwartz 2010), though this is likely a conservative approximation (Martin et al. 2015). The saturated soil infiltration capacity was also a conservative choice. The choice represents the worst case of the stormwater percolating into a porous pavement which has an underlying soil that is already saturated.

For underdrains, Murphey et al. (2014), found that their hydraulic performance could be modeled as an orifice. However, unlike the orifices for the green roof modules, if there are multiple underdrains they cannot simply be combined into one cumulative area and modeled as a single large orifice. This is because the orifices representing the underdrains are vertically orientated so increasing the area of the orifice, and thereby the diameter of orifice required, will also impact the height of the orifice area. Therefore, the underdrain size was calculated to be multiple 10.2 cm (4 in) porous pipes with an effective area of 81.1 cm^2 (12.6 in^2) that summed to the effective area needed to manage the peak discharge. Each of these underdrains was then represented by a separate orifice in the model. The weir at the top of the pavement is effectively an emergency overflow, and can be designed as a typical curb inlet for impervious pavements. Figure 4b shows an example of what the schematic of a porous pavement modeled in SSA looks like. Note that this pavement area required two underdrains, hence the two orifices.

Site LID implementation

As the three case study sites were actual developments, an engineering design firm provided the original post development models for each of the sites. The post-development model was then modified to create three additional models containing combinations of porous pavements and green-blue roofs. The first contained both technologies, the second just had porous pavements, and the third included just green-blue roofs.

For the addition of green-blue roofs to the model, any roof space in the post-development model was converted to a green-blue roof using the methods described above. For all the sites, the buildings were commercial or condominium style with flat roofs, so adding green-blue roofs was feasible. Similarly, since all the paved surfaces in the developments were parking lots or low traffic load roads, they were all modeled as porous pavement in the LID models.

Due to the layout of the sites, the models did include some area that was not part of the development but the runoff from these areas discharged to the pipe network being designed. For any area that was not part of the development and was completely isolated from the development hydrologically (e.g. the runoff flowed into the downstream pipe network just to account for pipe sizing downstream of the site) it was not included in the modeling. However there were some areas that came in upstream of the development or were combined in a subbasin with land that was in the development. In these cases the areas were included in the model but were not modified to include green roofs and porous pavements since they were not part of the development. This is predominately where the “other impervious areas” come from in Tables 1 and 2.

While the models used to capture the green-blue roof and porous pavement behavior in the stormwater modeling software are simple, they do add to the complexity of the overall model. Figure 5 shows the standard post development model (Figure 5a) compared to the same model with green-blue roofs and porous pavements included (Figure 5b). While the overall network stays the same, the number of components significantly increases as any subbasin that contains a green-blue roof or porous pavement has to be divided up and all the appropriate storage nodes, orifices, weirs, etc. must be added.

Model results

The six sub-site models that were developed had a range of pavement and roof areas (5.1 - 83.6% and 7.5 - 75.8% respectively). Since all the pavement and roof areas were converted to porous pavement and green-blue roofs for the different LID iterations of the model, there is a significant range of porous pavement and green-blue roof land area among the different sites. In the discussion of results the site with both green-blue roof and porous pavement is referred to as LID.

Each of the models were run using Soil Conservation Service (SCS) Type III 24 hour rainfall hyetographs with total depths ranging from 165 mm (6.5 in) (the 10 year 24 hour storm depth), up to 241 mm (9.5 in) which is 41 mm (1.6 in) greater than the current 25 year 24 hour design storm depth for the location of the sites modeled. Extending the storm depths modeled beyond the 25 year design storm is important as studies have shown that climate change will likely increase the storm depths of the 25 year design storm depths in South Carolina over the next century (Hutton et al. 2016).

Sample results

Figure 6 shows the results of the model runs for site B (Table 1). The four data series represent the four different development types namely traditional post development, LID, green-blue roof and porous pavement. For all development types both the peak runoff rate and the total runoff volume increase relatively linearly with storm depth. However, the slope of this linear relationship for the runoff rate increases for rainfall depths greater the current 25 year return period 24 hour storm (200 mm or 7.9 in). This would be expected as the sites were designed for this 25 year storm depth. For all rainfall depths the LID site had the lowest peak discharge followed closely by the green-blue roof design. The site with porous pavement only showed minimal reduction in peak discharge. While previous studies have shown that porous pavements can reduce peak discharge substantially (Luan et al. 2019) that is not the case for this site due to the low infiltration capacity of the soils and the relatively small percentage of the site area that has porous pavements installed (11.9% for this site). Conversely the green-blue roof does produce significant reduction in peak discharge due to the addition of the storage layer below the traditional green roof system. The peak discharge reduction of close to 50% at the level of a design storm has not been reported in previous studies of design storm performance. For example, Luan et al. (2019) only found an approximately 6-7% reduction in peak discharge for a site with the same percentage of its area covered in green-blue roof (62.4% for site B.) This is due to the blue-roof storage layer below the traditional modular green roof system that was implemented in the models for this study.

There is only a small reduction in total discharge for all designs. The green-blue roof does not have any significant impact on the total discharge. This is different from what is seen in field studies of smaller depth storms where moisture absorption into the soil and uptake by vegetation can represent a significant fraction of the storm depth. For example Morgan et al. (2013) reported that up to 50% of rainfall was retained over the course of an 18 month field study. Herein the worst case design state assumption that the soil is saturated at the start of the storm means that there is negligible water retention. In fact, given the modeling assumptions there should be no change in total runoff volume for the sites with green-blue roof as the only LID. The small changes (<4%) seen in the results are because, for some cases, the site was not fully drawn down at the end of the 72 hour simulation. Therefore, any changes in total runoff volume should be interpreted as having an uncertainty of $\pm 4\%$. This delay in drawdown does not impact the peak discharge as this occurs during the actual rainfall event and not during the drawdown period. The porous pavements do reduce the total discharge but for this particular site the difference is small as the percentage of the paved surface is relatively small (11.9%). In general, given the low infiltration capacity of the soils, the only retained volume is the storage volume below the underdrain invert.

To establish the relationship between the different development responses and to be able to compare the results across the different sites, these results were normalized using the traditional post development model. Figure 7 shows the same data as in Figure 6, but as a percentage of the traditional post development model. Now rather than seeing the general trend of the peak runoff rate increasing as a function of rainfall depth, Figure 6a shows that the developments incorporating LID technologies stayed at a relatively constant percentage of the traditional post development rate for rainfall events below the current 25 year design storm (200 mm or 7.9 in). However, above that depth they started to converge toward the traditional development runoff rate. The behavior of the total discharge is similar although the percentage reductions are considerably smaller as they are only due to the 11.9% of the site on which porous pavements were installed.

It is important to note that these figures are representing a specific site so no conclusions should be drawn from these about the effectiveness of LID for another specific development. For example, from Figures 6 and 7 it appears that green-blue roof is exceedingly good at reducing peak discharge while porous pavements have only a marginal benefit. However this conclusion is biased as 62.4% of the site is roof area while only 11.9% of the site is pavement area. These figures are more useful in illustrating the general trends and relationships.

Comparison of performance across all sites

To examine the impact of the different percentages of land area installed with each LID technology all the sites' peak discharge and total volume results were compiled by development type: LID (green-blue roof and porous pavements), green-blue roof only, and porous pavements only and plotted as fractions of the standard site development results. These data are shown in Figure 8.

Figure 8 shows the ranges that could be expected from typical sites. While the area of land devoted to each LID technology varies between sites (causing the broad range), it is apparent that green-blue roofs (Figure 7a) tend to have a significant impact on peak discharge due to the large storage volume available in the blue-roof portion of the modular green-blue roof system. However, porous pavement does not have as large an impact on peak discharge (Figure 8b), though they do still have some impact on the peak discharge especially when there is a large enough area. For example, the porous pavement on site 6 (Figure 8b) has a peak discharge around 60% of the standard post development peak discharge due to its large pavement area (83.4% of the site).

The lack of impact from the porous pavement when it is a smaller fraction of the surface area is due to the pavement storage capacity being mostly filled before the peak in the storm's rainfall intensity. This is mostly due to the low infiltration rate of the soils on these sites. Higher infiltration soils could result in the pavement not filling prior to the peak rainfall intensity which would result in a more significant reduction in peak discharge. However, this study shows that porous pavements, even placed over lower infiltration capacity soils, could significantly reduce peak discharge for shorter duration high intensity storms provided the storm depth could be stored in the pavement sub-layers below any underdrains.

The reduction in total volume for each development type is shown in Figure 9. While the green-blue roofs models used in this study are designed to increase detention, they don't retain any water as explained in Martin et al. (2020) and Martin and Kaye (2020). Due to this they have negligible impact on the total volume discharged from a site and any changes in total volume seen in Figure 9a can be attributed to incomplete drawdown as noted earlier.

Porous pavements are infiltration based and as such they do have a potentially large impact on the total volume of runoff. As discussed above with the peak discharge, the broad range of modeled reductions is due to the large range of pavement areas across the individual sites. It is interesting to note the general trend of the increasing percentage of total volume as the rainfall depth increases. This is because the volume of these porous pavements is static and once the soil's infiltration capacity has been fully utilized the porous pavement cannot contribute more to volume reduction. Therefore any additional rainfall will become runoff and, as rainfall depths increase, everything will converge toward the traditional development results. This trend is very clearly seen for these sites as all the sites have low infiltration soil that allow only smaller storms to completely utilize the infiltration capacity. For sites with higher infiltration soils the infiltration capacity of the soil would not be reached until much larger rainfall depths.

In the case of the LID development (green-blue roof and porous pavements), the results are almost identical to that of the site with only porous pavements. This is as expected as the green-blue roof does not impact the total volume discharged from the site.

Performance of LID in a changing climate

Climate models have predicted that climate change will result in larger, more frequent rainfall events (IPCC 2001). When design storm depths were calculated using the climate model results for South Carolina, the 25 year design storm was predicted to increase by 10 to 23 mm (0.4 to

0.9 in) over the next 85 years (Hutton et al. 2016). Because the LID technologies modeled herein can reduce peak runoff and retain runoff volume, they have the potential to offset the increases in runoff due to larger storm depths. To quantify this impact, the peak discharge (or total volume) of the standard post-development site was determined for the current 25 year storm depth. Then the point at which each of the other development types match the same peak discharge (or total volume) was identified and the rainfall depth of this point was recorded. The difference between the original 25 year storm depth and the new rainfall depth is the amount that rainfall depths could increase before a particular LID development type would experience the same runoff as the standard development at the current 25 year storm depth.

Figure 10 shows this process schematically for the development type with only porous pavements for site S1. The traditional model predicted a peak discharge of 1.3 m^3/s (46 cfs) for a 203 mm (8 in) (approximately the 25 year 24 hour design storm for this location). The porous pavement only model will not reach this level of peak discharge until it is subjected to a 218 mm (8.6 in) of rainfall, 15 mm (0.6 in) more than the current 203 mm (8 in) design storm (a 7.5% increase).

This calculation was run for both peak discharge and total runoff volume for the 6 green-blue roof sites and 6 porous pavement sites. The results of these calculations yields a storm depth percent change value for both peak discharge and total volume for each development type for each site. Figure 11 shows the percentage increase in rainfall depth that can be accommodated for peak discharge and total volume parity as a function of the percentage of the development site covered by either porous pavements of green-blue roofs. Peak discharge (figure 11a) is reduced by both porous pavement and green-blue roofs, but green-blue roofs have a larger impact for the same coverage areas. Total volume is not impacted by the inclusion of green-blue roofs (figure 11b). However, porous pavements do have a significant impact.

Figure 11a shows that the inclusion of green-blue roof systems can substantially increases the design capacity of the stormwater infrastructure to accommodate substantially larger storms than current design storms. For the sites modeled, even only 20% of the site covered in green-blue roof results in a 20% increase in the design storm capacity compared to a standard impervious roof. Again, this is due to the storage layer portion of the green-blue roof that acts as a distributed detention pond on the rooftop. Figure 11b shows that porous pavement can reduce total discharge even when installed over poor infiltration rate soils. However, the performance increase is substantially less than that measured for peak discharge reduction for green-blue roof. For example, for the same 20% installation area the total volume will match the current standard development volume at storm depths 3-9% in excess of current design depths.

Discussion & conclusions

The model results above show that the use of green-blue roof and porous pavements, when appropriately designed, can have a significant impact on stormwater runoff from land developments. Further, such designs could be used to mitigate the impact of increasing frequency and intensity of extreme storms. Green-blue roof systems add significant rooftop storage capacity that, combined with an appropriately sized outlet control, can significantly reduce rooftop peak discharge. This reduction is due to the large storage volume that can be placed on the rooftop for large area roofs. Green-blue roof systems provide negligible reduction in total discharge for design storm events of the order modeled herein (165 mm or 6.5 in of rainfall and deeper). The modular nature of green-blue roof systems enables them to be used to retrofit existing buildings, provided the building structure is capable of supporting the additional dead load due to the weight of the green roof system, and live load due to the water detained in the system during a rainfall event. The use of green-blue roof as retrofits could be used to offset the impact of climate change induced increases in design storm depth. For example, the data in figure 11(a) shows that even adding a small green-blue roof system representing 20% of the plan area of a site can still enable the site to manage a 20% increase in design storm depth while maintaining the original peak discharge from the site. The key is to include the storage layer below modular green roof system. In the absence of this layer modular green roof systems provide negligible peak discharge reduction for large design storm depths (Martin et al. 2020).

Porous pavements were shown to primarily reduce the total discharge volume from a site but had a smaller, though not insignificant, impact on the peak discharge for the site models considered. The reduction in total runoff volume is due to infiltration of water into the underlying soil. For the sites modeled herein, the soil infiltration capacity was quite low. For higher infiltration capacity soils, the reduction in total runoff volume will be more significant. While the porous pavements did reduce peak discharge, its impact was not as significant as green-blue roofs for two main reasons. First, porous pavement systems are primarily infiltration devices rather than flow attenuation technologies. Second, given the poor infiltration capacity of the soils on the sites modeled, the pavements required a significant number of underdrains (see figure 4b). The drains were located at a height such that the pavement would completely drawdown within 72 hours of the storm (based on SC DHEC requirements (SCDHEC 2002)) and sized to ensure that the pavement did not overtop for the 25 year storm. However, this meant that the underdrains were always fully submerged at the time of the peak rainfall intensity leaving little capacity for peak flow attenuation. Again, improved soil infiltration capacity will reduce the number of required underdrains enabling the porous pavement to be more effective in peak flow attenuation. However, despite the poor infiltration capacity of the soil there is still significant benefit to the total discharge attained by implementing porous pavement provided there is an appropriately sized and located set of underdrains. Therefore, porous pavements could be considered for use over a broader range of soils provided that the underdrains are carefully sized and located.

It is important to note that these results are specific to this location and designs. In areas with lower rainfall depths or better soils, better performance would be expected in regard to peak discharge and total volume reduction. Also specific design changes can be made to the green roof and porous pavements to better target ideal performance. These include increased storage volumes and staged outlets to improve performance for smaller design storms. Herein the modeling focused on using a common set of design depths for the green-blue roof (102 mm or 4 in for the module and storage layer thickness) and porous pavement (178 mm or 7 in subbase and 127 mm or 4 in pavement thickness) and then tailoring them to each site by altering the outlet area for the green-blue roof and the underdrain sizes and locations for the porous pavement. Substantially improved performance could be realized by using larger storage depths where possible.

The models used in this case study were not calibrated against specific measurements or observations at the sites modeled. The results are, therefore, indicative of the relative performance of the LID technologies rather than for final design purposes. Full design implementation would require more detailed analysis of the site specific soil properties and other key parameters. However, the modeling approaches used in the study are based on techniques in the literature. See Murphy et al. (2014) for pavement underdrain hydraulics, Martin et al. (2015) for soil masking, Schwartz (2010) for porous pavement routing, and Martin at al. (2020) for green roof hydraulics. As such, the model relative performance data presented will be indicative of site relative performance of the different LID technologies.

The use of porous pavement systems and modular green-blue roofs has the potential to significantly reduce peak and total discharge from a land development even for low infiltration capacity soils. This in turn could make sites more resilient to a changing climate. The inclusion of green-blue roofs and porous pavement into site design can offset the increase in design storm depth that many global climate models predict (Hutton et al. 2016). The design methodologies and modeling approach presented herein will enable engineers to design stormwater management systems that require less land area to be used for ponds and other end-of-pipe management systems and that are more resilient to increases in extreme storm frequency and depth. The reduction in land area required for stormwater infrastructure will allow for the development of a larger fraction of the site which could potentially offset the additional cost of using porous pavement and green-blue roof systems.

Data Availability

All data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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