The Effectiveness of Centralized versus Decentralized Green Infrastructure in Improving Water Quality and Reducing Flooding at the Catchment Scale

Katherine Meierdiercks and Nicholas McCloskey

Siena College, Loudonville, New York.

Abstract

Green infrastructure (GI), such as green roofs, rain gardens, and porous pavement, is a stormwater management strategy designed to capture rain where it falls and allow it to soak into the ground rather than running off into a stream channel, thus reducing flooding and improving water quality. While there has been a lot of research into the performance of individual GI projects, much less is known about its performance at the catchment scale. This study uses a US EPA SWMM model to examine the effectiveness of GI in improving water quality and reducing flooding at the catchment scale. Results show that in the study catchment, a large centralized wetland was the most effective at reducing and slowing peak discharge. Infiltration based decentralized GI best reduced flood volumes. In addition to changes in effective impervious area, flood volumes were also reduced due to differences in drainage network structure and modifications to the pervious portions of the catchment. Reductions in flood volumes resulted in lower pollutant loads, except for pollutants that are particularly efficiently removed by wetlands. Routing runoff through a large, centralized wetland removed more nitrate load than letting rain infiltrate where it falls.

1 Introduction

Flooding and poor water quality in urban areas are typically caused by impervious surfaces such as roads, buildings and parking lots (Leopold 1968; Schueler 2003). These hard surfaces prevent rain from soaking into the ground. As rain runs off over the land surface, it takes with it pollutants that eventually enter the surface water system. Green stormwater infrastructure (GI), also referred to as low impact development (LID) (Fletcher et al. 2015), is a strategy that can be used to prevent flooding and improve water quality by capturing rain where it falls. GI strategies such as green roofs, rain gardens, and porous pavement can also provide ecosystem services and human health benefits (Coutts and Hahn 2015). Stormwater wetlands, defined by the US EPA as landscape or watershed level GI (US EPA 2021), are often designed to detain runoff during storm events and release it slowly, but can also promote infiltration and evaportranspiration.

Many studies have examined the performance of individual GI projects (Hathaway et al. 2008; Sychten et al. 2014; Shuster et al. 2017; and Chowdhury and Abaya 2018 are among the many examples). While a single GI project can effectively reduce flooding and improve water quality, work that summarizes and synthesizes these studies suggests that the effectiveness of any given site level GI project often depends on the type of GI examined, site characteristics, and the pollutant of concern (Center for Watershed Protection 2007; Koch et al. 2014; Leisenring et al. 2014). Furthermore, the scaling of the performance of GI practices from individual or lot scales to catchment scales is not well understood (Ahiablame et al. 2012; Golden and Hoghooghi 2018).

Catchment scale GI performance can be evaluated by collecting flooding and water quality data in the field. This requires monitoring a watershed before and after implementation of GI (Shuster et al. 2013) or through multi-watershed studies (Pennino et al. 2016). At the neighborhood scale, some paired-catchment studies have shown that GI within a residential development can reduce runoff and improve water quality (Dietz 2007; Dietz and Clausen 2008; Hood et al. 2007), yet similar studies have shown that GI cannot mitigate the impacts of residential development and the associated impervious surfaces (Yang and Li 2013). Multi-watershed studies have found that pollutant loads were lower in watersheds with more GI (Pennino et al. 2016), and Loperfido et al. (2014) found that a watershed with distributed GI reduced runoff volumes and peaks better than a paired watershed with centralized GI, but more work is needed to assess whether these results are consistent across geographic regions (Jefferson et al. 2017; Golden and Hoghooghi 2018). Jefferson et al. 2017 also note confounding factors can complicate the interpretation of catchment scale field studies.

An alternative approach to empirical and field studies for assessing catchment scale GI performance is to use a rainfall–runoff model (see for example Di Vittorio and Ahiablame 2015; Carvallo Aceves et al. 2017). As with site level studies, the results
of these modeling studies also vary with GI type, site and pollut-
ant as well as land use type and location (Jefferson et al. 2017).
Scale dependence on the performance of GI at the watershed
scale (Javier et al. 2007; Meierdiercks et al. 2010) may explain
some of the inconsistencies (Smith et al. 2015).

Many studies have pointed to the need to better under-
stand the cumulative impact of GI on the catchment scale (Fahy
and Change 2019; Golden and Hoghooghi 2018; Loperfido et al.
2014, for example). While it is generally understood that as the
percentage of the watershed treated by GI increases, so do the
hydrological and water quality benefits (Jefferson et al. 2017)
as the percentage of effective imperviousness decreases (Palla
and Gnecco 2015). However the cumulative impact of the spatial
configuration of GI, particularly centralized versus distributed
GI, is less straightforward. Catchment scale modeling studies
suggest that centralized GI can reduce flood peaks and volumes
when storage capacity or watershed capacitance is not exceeded
(Lim and Welty 2017), but distributed GI may be more effective
when runoff volume exceeds the storage capacity of centralized
GI (Antolini and Tate 2021; Fahy and Chang 2019). More work is
needed to better understand the cumulative impacts of GI, par-
ticularly on water quality, at the catchment scale. This study ad-
dresses these research gaps through the following objectives: (1)
to use a stormwater model to examine the impacts of GI (green
roofs, wetlands and soil management improvements) on water
quality and flooding in the study catchment; and (2) to identify
performance differences between centralized versus decentral-
ized GI in the study catchment.

2 Methods

2.1 Study area

The study area for this project was the Siena College campus
catchment (Figure 1), a subwatershed of the larger Kromma Kill
Watershed. The 0.86 km² study area is 23% impervious (covered
by roads, buildings, and parking lots) and contains five storm-
water wetlands (P-1, P-2, P-3, P-5, and P-6 in Figure 1) and one
detention pond (P-4). The total 8.7 km drainage network consists
of 95% pipes and 5% surface channels. The predominant soil type
is loamy sand. Of the 0.20 km² of impervious surfaces in the study
area, 11.5% are buildings. The Kromma Kill stream channel ori-
ginates on campus and flows 4.8 km downstream to the Hudson
River. The Kromma Kill is an impaired waterbody and prone to
flooding and other water quality problems. Though polychlorin-
ated biphenyls (PCBs) and heavy metals have been detected in
the sediments downstream of the study area, near a Brownfield
site (Al Tech Specialty Steel, Site Code 401003), according to water
quality sampling during 2014 and 2015, runoff from campus is
typical of institutional dominated land uses. For example, during
2014 baseflow sampling, nitrate and total nitrogen concentra-
tions were higher than other sampling sites throughout the area,
but still well below the New York State Department of Environ-
mental Conservation’s standards for aquatic health.

Figure 1 Map of the study area.

2.2 Model development

A US EPA SWMM v5.1 stormwater model was built from field
observations and geospatial datasets for the study area (Table 1,
Meierdiercks et al. 2017). See James et al. (2010) for a full de-
scription of the mathematical equations used by SWMM. Field
observations of rainfall were used as model forcing, and stream-
flow and water quality measurements were used to calibrate the
model. The model was then modified to represent several design
scenarios. In each scenario, one or more GI strategies were added
to or removed from the catchment and the impact on water
quantity and quality was examined.

The 0.86 km² study area includes the main catchment
(0.52 km²) that drains to the outlet indicated in Figure 1. Seven
additional subareas (ranging in size from 0.008 km² to 0.1 km²)
were included in model simulations. Each subarea drains to an
outlet which then flows to the main Kromma Kill stream channel.
Subareas are further divided into subcatchments ranging in size
from 61.5 m² to 97 700 m² (average 8390 m²) and in percent
impervious from 0 to 88.5% (average 27.7%). Both the impervious
and pervious areas of each subcatchment runoff directly into the
storm drain network (subarea routing to the outlet).

The model includes a large centralized stormwater wet-
land, 4 additional smaller wetlands, and 1 stormwater detention
pond (Table 2). The stormwater wetlands and detention pond
were modeled in SWMM as storage units with removal efficien-
cies (Table 3) determined from Leisenring et al. (2014). The vol-
ume of the wetlands were determined from 61 cm (2 ft) contour
lidar-derived topography data. Outflow was modeled using a
depth based rating curve provided in stormwater pond design
Table 1 SWMM model parameters.

| Parameter                  | Type      | Value                      | Source                          |
|----------------------------|-----------|----------------------------|---------------------------------|
| Rain gauges                | Input/forcing | 2.24 cm, 4.04 cm and 7.04 cm | from: http://precip.eas.cornell.edu/ |
| Area                       | Model     | Variable                   | Measured using GIS              |
| Width                      | Model     | Variable                   | Measured using GIS              |
| % Slope                    | Model     | Variable                   | digital elevation model from Albany County, NY, Computed using 30 m NLCD 2011, verified and corrected as needed using aerial photos |
| % Imperv                   | Model     | Variable                   | Calibration parameter           |
| N-Imprv                    | Model     | 0.02                       | Calibration parameter           |
| N-Perv                     | Model     | 0.3                        | Calibration parameter           |
| %Zero-Imprv                | Model     | 25                         | James et al. (2010)             |
| Subarea Routing            | Model     | OUTLET                     | Observed in the field           |
| Percent Routed             | Model     | 100                        | Observed in the field           |
| Node location and geometry | Model     | Variable                   | Siena College stormwater pipe data |
| Link location and geometry | Model     | Variable                   | Siena College stormwater pipe data and Albany County lidar derived 2 ft contour data from: http://precip.eas.cornell.edu/ |
| Storage unit geometry      | Model     | Variable                   | data                            |
| Storage unit outlet geometry | Model   | Variable                   | Siena College stormwater pond design data |
| Infiltration               | Model     | Green–Ampt                 | NA                              |
| Suction Head               | Model     | 6.096 cm (2.4 in.)         | Value for loamy sand (James et al. 2010) |
| Conductivity               | Calibration | 4.7625 mm/h               | Calibration parameter           |
| Initial Deficit            | Calibration | 0.146                   | Calibration parameter           |
| TN EMC (mg/L)              | Calibration | 2.1                      | James et al. (2010)             |
| TDS EMC (mg/L)             | Calibration | 178.1                    | Measured in the field           |
| NO₃⁻ EMC (mg/L)            | Calibration | 1.46                     | Measured in the field           |
| TP EMC (mg/L)              | Calibration | 0.263                    | James et al. (2010)             |

Table 2 Stormwater pond dimensions.

| Name              | Surface area (m²) | Max depth (m) | Max outflow (m³/s) | Depth of max outflow (m) |
|-------------------|-------------------|---------------|--------------------|--------------------------|
| P-1 Wetland       | 2530              | 2.13          | 2.36               | 1.1                      |
| P-2 Wetland       | 2500              | 0.61          | 0.184              | 0.61                     |
| P-3 Central wetland | 18,200            | 7.32          | 1.61               | 1.58                     |
| P-4 Detention pond | 662               | 1.23          | 0.55               | 1.23                     |
| P-5 Wetland       | 232               | 0.305         | No outlet          | NA                       |
| P-6 Wetland       | 502               | 0.305         | No outlet          | NA                       |
| Decentralized wetlands (9) | 6080 | 2.54          | 0.18               | 0.521                    |

Table 3 Pollutant removal efficiencies (Leisenring et al. 2014).

|                | TN     | TDS    | NO₃⁻   | TP     |
|----------------|--------|--------|--------|--------|
| Wetland        | −0.053 | −0.75  | 0.73   | 0.46   |
| Stormwater Pond | −0.21  | 0.052  | 0.18   | 0.22   |

The calibrated model was then modified to represent a number of alternative design scenarios (Figure 2, Table 5) to test the relative impact on water quality and quantity of centralized versus decentralized and detention based versus retention based GI at the catchment scale. For the decentralized wetlands scenario, the large centralized wetland was replaced with 9 smaller wetlands, each with 11.11% of the volume of the wetland. The outlet rating curve was modified so each decentralized wetland provided 11.11% of the outflow of the centralized wetland. Two decentralized wetlands scenarios were tested. The first keeps the distribution of impervious surfaces in the catchment the same as in the centralized scenario. In the centralized scenario, 0.39 km² (31.5% impervious) is captured. In the decentralized scenario, 0.13 km² (23% impervious) is captured. For the second decentralized wetlands scenario, all impervious areas that were upstream of the centralized wetland are moved upstream of the decentralized wetlands, therefore keeping the area of imperviousness treated the same. This results in an upstream imperviousness of 92.1%. For the green roof, parameters were chosen to match those in Rossman (2010) and typical values found in green roof design and construction resources (Table 6). The model was also run using SWMM green roof input parameters as described in Hamouz and documentation.
Results were analyzed quantitatively by examining the impact of each model scenario compared to the BAU scenario on peak flooding, flood volumes, and pollutant outflow concentration and load. To compare water quantity volumes, the runoff ratio was calculated as surface runoff divided by total precipitation. Peak discharge was determined from the system outflow hydrograph and time to peak was computed as the time between peak rainfall and peak discharge. System outflow refers to the total outflow from the main study area catchment as well as the additional subareas shown in Figure 1. System outflow was presented so that areas of the study catchment not controlled by the centralized wetland would be included in the results. For water quality, external outflow pollutant load (in lbs) and external outflow concentration (outflow pollutant load in lbs divided by external outflow flow volume) were examined.

System outflow hydrographs for each model scenario using the 60 min 1 y, 10 y, and 100 y design storms are shown in Figure 3. For the 1 y storm, the BAU scenario (large, centralized wetland) resulted in the smallest peak discharge and longest time to peak (Figure 3, Table 7). Removing the large, centralized wetland increased peak discharge by 129.7% and decreased the time to peak by 36.0%, while the decentralized wetlands also led to a 36.0% decrease in time to peak and a 109.4% increase in peak discharge. The decentralized wetlands (upstream imperviousness), decentralized green roofs and improved soil management scenarios all resulted in similar increases in peak discharge (respectively 62.4%, 70.5%, and 64.7%). The decentralized wetlands (upstream imperviousness) only slightly increased the time to peak (8%), while the decentralized green roofs and
soil management scenarios decreased time to peak respectively by 32.0% and 72.0%.

The impacts on peak discharge and time to peak compared to the BAU scenario were similar as the storm size increased to the 10 y and 100 y storms (Table 7). The exception is the impact of the better soil management scenario on peak discharge. For the 1 y storm, the better soil management scenario led to a 64.7% increase in peak discharge compared to the BAU scenario. However, for the 10 y storm, the peak discharge decreased by 8.2% and for the 100 y storm, it increased by 5.1%. The control, decentralized wetlands, decentralized wetlands (upstream imperviousness), and decentralized green roofs scenarios increased peak discharge by 91.5%, 74.8%, 62.4% and 58.3%, respectively, for the 10 y storm and by 97.1%, 77.2%, 69.8%, and 71.1%, respectively, for the 100 y storm. For time to peak, the control, decentralized wetlands, decentralized wetlands (upstream imperviousness), decentralized green roofs, and soil management scenarios increased time to peak by 19.2%, 19.2%, 11.5%, 19.2%, and 65.4% (10 y storm), and 62.8%, 39.5%, 53.5%, 62.8%, and 60.5% (100 y storm) compared to the BAU scenario.

Table 7 Results of SWMM water quantity modeling.

| Model Scenario                             | Peak Discharge (m³/s/km) | % Change | Time to Peak (min) | % Change | Runoff Ratio | % Change |
|--------------------------------------------|--------------------------|----------|-------------------|----------|--------------|----------|
| 1 y storm                                  |                          |          |                   |          |              |          |
| Business as Usual (large, central wetland) | 0.9                      | –        | 25                | –        | 0.27         | –        |
| Control (no wetland, no GI)                | 2.1                      | 129.7%   | 16                | −36.0%   | 0.29         | 6.9%     |
| Decentralized wetlands                     | 2.0                      | 109.4%   | 16                | −36.0%   | 0.28         | 1.5%     |
| Decentralized wetlands (upstream imperviousness) | 1.5                     | 62.4%    | 23                | −8.0%    | 0.24         | −12.2%   |
| Decentralized green roofs                  | 1.6                      | 70.5%    | 17                | −32.0%   | 0.21         | −21.2%   |
| Soil management                            | 1.5                      | 64.7%    | 7                 | −72.0%   | 0.16         | −42.6%   |
| 10 y storm                                 |                          |          |                   |          |              |          |
| Business as Usual (large, central wetland) | 2.6                      | −        | 26                | −        | 0.47         | −        |
| Control (no wetland, no GI)                | 5.0                      | 91.5%    | 21                | −19.2%   | 0.48         | 1.1%     |
| Decentralized wetlands                     | 4.6                      | 74.8%    | 21                | −19.2%   | 0.44         | −7.5%    |
| Decentralized wetlands (upstream imperviousness) | 4.3                     | 62.4%    | 23                | −11.5%   | 0.44         | −6.8%    |
| Decentralized green roofs                  | 4.2                      | 58.3%    | 21                | −19.2%   | 0.38         | −19.7%   |
| Soil management                            | 2.4                      | −8.2%    | 9                 | −65.4%   | 0.16         | −66.1%   |
| 100 y storm                                |                          |          |                   |          |              |          |
| Business as Usual (large, central wetland) | 4.7                      | −        | 43                | −        | 0.58         | −        |
| Control (no wetland, no GI)                | 9.2                      | 97.1%    | 16                | −62.8%   | 0.59         | 1.9%     |
| Decentralized wetlands                     | 8.3                      | 77.2%    | 26                | −39.5%   | 0.53         | −8.6%    |
| Decentralized wetlands (upstream imperviousness) | 7.9                     | 69.8%    | 20                | −53.5%   | 0.53         | −8.2%    |
| Decentralized green roofs                  | 8.0                      | 71.1%    | 16                | −62.8%   | 0.48         | −18.0%   |
| Soil management                            | 4.9                      | 5.1%     | 17                | −60.5%   | 0.25         | −57.4%   |

The runoff ratios for each model scenario are shown in Table 7. While the BAU scenario resulted in the smallest peak discharges (with the exception of the 10 y soil management scenario) and longest time to peak, it did not result in the smallest runoff ratio. In terms of runoff volumes, for the 1 y storm, the soil management scenario led to the greatest reduction of runoff volume, followed by the decentralized green roofs, and decentralized wetlands (upstream imperviousness) (respectively 42.6%, 21.2%, 12.2%). The decentralized wetlands and control scenarios both led to increases in runoff volumes compared to the BAU scenario (respectively 1.5% and 6.9%).

As storm size increased to the 10 y and 100 y storm, the soil management followed by the decentralized green roof scenarios reduced the greatest volume of runoff (respectively 66.1% and 19.7% for the 10 y storm, and 57.4% and 18.0% for the 100 y storm). There was less of a difference in runoff ratio between BAU and control scenarios (respectively 1.1% and 1.9%, compared to 6.9% for the 1 y storm). For the 1 y storm, the decentralized wetlands increased runoff volumes by 1.5%, but reduced volumes by 12.2% when the decentralized wetlands were paired with impervious surfaces concentrated upstream of the wetlands. For the 10 y and 100 y storms, both decentralized wetlands scenarios resulted in similar reductions of runoff volume: 7.5% and 6.8% for the 10 y storm, and 8.6% and 8.2% for the 100 y storm.

Figure 3 System outflow hydrographs for the 1 y (top), 10 y (middle), and 100 y (bottom) storm SWMM model scenarios.
Additional calculations were made to compare runoff volumes generated as part of each of the three wetland scenarios. A detailed discussion of these results is provided in the next section. The runoff ratios for each wetland scenario, computed as the volume of outflow from the wetland divided by the volume of rainfall upstream of the wetland, are shown in Table 8. Each scenario resulted in a runoff ratio that was greater than the system outflow runoff ratio and that was close to or exceeded the impervious percentage upstream of the wetland or wetlands. The final stored volume (defined as the total volume of water remaining in storage units, pipes, and nodes at the end of the simulation) plus the losses due to flooding (defined as the water that lost to the system when nodes flood more than the 4.6 m² allowable ponded area) as a fraction of the total rainfall was computed for each wetland scenario. This is the percentage of rainfall that neither infiltrates nor leaves the study area as outflow. For the BAU (centralized wetland) scenario, these values are: 10.1%, 10.2%, and 15.1% (respectively 1 y, 10 y, 100 y storms); for the decentralized wetlands scenario: 10.2%, 13.9%, and 20.2% (respectively 1 y, 10 y, 100 y storms); and for the decentralized wetland scenario where imperviousness surfaces are moved upstream: 13.1%, 12.7%, 19.8% (respectively 1 y, 10 y, 100 y storms). For comparison, for the control scenario, the percentages of rainfall remaining in storage and lost to flooding are: 8.1%, 9.7%, and 14.0% (respectively 1 y, 10 y, 100 y storms). For all scenarios, the percentages of rainfall remaining in storage and lost to flooding increased as storm sizes increases. The centralized wetlands scenario resulted in more rainfall remaining in storage or lost to flooding than the control scenario, but less than the decentralized wetlands scenarios.

Table 8 Runoff ratios for wetland model scenarios; runoff ratio is computed as the storm total rainfall divided by the runoff generated downstream of the central wetland or representative decentralized wetland.

| Model Scenario                        | Upstream imperviousness | 1 y storm Runoff ratio | 10 y storm Runoff ratio | 100 y storm Runoff ratio |
|---------------------------------------|-------------------------|------------------------|-------------------------|-------------------------|
| Business as Usual (large, central wetland) | 31.5%                   | 0.43                   | 0.64                    | 0.76                    |
| Decentralized wetlands                | 23.3%                   | 0.7                    | 0.8                     | 0.9                     |
| Decentralized wetlands (upstream imperviousness) | 92.1%                   | 0.9                    | 0.9                     | 1                      |

The outflow concentration and loading for each model scenario for the 1 y storm are shown in Table 9. Removing the large centralized wetland increased both the pollutant concentration and load. Replacing the large, centralized wetlands with smaller decentralized ones, when the distribution of impervious surfaces was kept constant, resulted in TN and TDS concentration and loads slightly decreasing (−4.0% and −2.6% for TN, −5.0% and −3.6% for TDS), but NO$_3^-$ and TP concentration and loads increasing considerably (78.7% and 81.3% for NO$_3^-$, 29.5% and 31.4% for TP). Water quality improvements were similar for the decentralized wetlands with the impervious surfaces concentrated upstream of the wetlands: TN and TDS concentration increased and loads decreased slightly (6.7% and −6.3% for TN, 6.5% and −6.5% for TDS), but NO$_3^-$ and TP concentration and loads considerably increased (84.7% and 62.2% for NO$_3^-$, 39.3% and 22.3% for TP). The infiltration based scenarios, decentralized green roofs and soil management, led to water quality improvements for TN and TDS concentration and load, but poorer water quality for NO$_3^-$ concentration and load. For TP, load improved, but water quality concentration declined compared to the BAU scenario.

Table 9 Results of SWMM water quality modeling for the 1 y design storm; negative percentage change values indicate water quality improvements.

| Model Scenario                        | TN % change | TDS % change | NO$_3^-$ % change | TP % change |
|---------------------------------------|------------|--------------|-------------------|------------|
| Business as Usual (large, central wetland) | 7.8%       | 7.9%         | 127.4%            | 59.2%      |
| Control (no wetland, no GI)           | −2.6%      | −3.6%        | 81.3%             | 31.4%      |
| Decentralized wetlands                | −6.3%      | −6.5%        | 62.2%             | 22.3%      |
| Decentralized wetlands (upstream imperviousness) | −37.8%    | −39.6%       | 27.0%             | −11.1%     |
| Soil management                       | −44.4%     | −43.2%       | 20.6%             | −15.4%     |

The impacts on water quality concentration and loading are similar for the 10 y and 100 y storms (see Tables A1 and A2). Scenarios that led to a difference of more than 20 percentage points between the 1 y and 10 y storms include the decentralized wetland scenario, where the percentage change in NO$_3^-$ concentration increased from 78.7% to 111.0% (less water quality improvement), and the soil management scenario, where the percentage change in TN, TDS, NO$_3^-$, and TP load decreased from...
located in higher flow accumulation areas. Centralized stormwater management was most effective when watershed capacitance was not exceeded. In this study and ours, smaller runoff ratios associated with the decentralized wetland remained constant, the runoff ratio decreased by 12.2% compared to the decentralized wetland scenario. As storm size increased from the 1 y to the 10 y and 100 y storms, both decentralized wetland scenarios resulted in smaller runoff ratios (between 6.8 and 8.6%) compared to the centralized wetland scenario. However, the smaller runoff ratios associated with the decentralized wetland scenarios were not due to added storage capacity or increased infiltration: the total volume of the 9 decentralized wetlands is equivalent to that of the large, centralized one and the decentralized wetlands did not retain runoff any more effectively than the centralized wetland (Table 8). Instead, the larger runoff ratio of the centralized wetland is due to the long tail of the system outflow hydrograph (Figure 3) as the large centralized wetland slowly drains long after the end of the 1 h duration storm. The smaller, decentralized wetlands drain equally slowly, but that outflow entered into the storm pipe network rather than a surface channel as in the centralized wetland scenario. The pipe network has smaller storage and flow capacities than the surface channel, so outflow from the decentralized wetlands was attenuated and dispersed as it moved through the drainage network. As a result, the final stored volume plus flood losses for the decentralized wetlands scenarios was greater than that of the centralized wetland scenario (i.e. more water was lost to and remains in the drainage network at the end of the simulation compared to the centralized wetland scenario). Results highlight the complexity of hydrologic response in urban watersheds and the importance of considering the impact of drainage network structure in catchment scale urban flood studies (Meierdiercks et al. 2010).

4 Discussion
Jefferson et al. 2017 note that traditionally large centralized greywater stormwater management strategies such as detention ponds were used to manage stormwater, but more recently decentralized or distributed infiltration based GI such as rain gardens and green roofs have grown in popularity. However, there are relatively few studies that have examined the cumulative impact of centralized versus decentralized GI, particularly the impact on water quality, at the catchment scale. In the following section, we discuss the results of this study, specifically the cumulative impacts on catchment scale water quantity and quality of (1) centralized versus decentralized wetlands, and (2) detention versus retention based decentralized GI.

4.1 Centralized versus decentralized wetlands
In the study catchment, the large centralized wetland is specifically designed to slow and detain runoff from large storms. Results suggest that the wetland is functioning as designed. For peak flows in the study catchment, the centralized wetland reduced and slowed peak flows for the 1 y, 10 y, and 100 y storms, more than the decentralized wetlands scenarios, even when the area of impervious treated and storage capacity is kept constant. This result is consistent with Lim and Welty 2017 who found that centralized GI performed better in catchments where storage capacity or watershed capacitance was not exceeded. In this study and ours, centralized stormwater management was most effective when located in higher flow accumulation areas.

In terms of flow volumes, for the 1 y storm, the runoff ratios for the centralized and decentralized wetland scenarios were very similar (only a 1.5% difference). But when the distribution of impervious surfaces is modified and moved upstream of the decentralized wetlands so that the area of impervious surfaces treated remains constant, the runoff ratio decreased by 12.2% compared to the centralized wetland scenario. As storm size increased from the 1 y to the 10 y and 100 y storms, both decentralized wetland scenarios resulted in smaller runoff ratios (between 6.8 and 8.6%) compared to the centralized wetland scenario. However, the smaller runoff ratios associated with the decentralized wetland scenarios were not due to added storage capacity or increased infiltration: the total volume of the 9 decentralized wetlands is equivalent to that of the large, centralized one and the decentralized wetlands did not retain runoff any more effectively than the centralized wetland (Table 8). Instead, the larger runoff ratio of

4.2 Decentralized detention based versus infiltration based GI
For the study catchment, when comparing the decentralized wetlands (detention) versus decentralized green roofs (retention or infiltration), as expected, the green roof scenario reduced volumes more than either of the decentralized wetlands scenarios for all storm sizes. With the reductions in volume, for all storm sizes, the decentralized green roof scenario resulted in similar or smaller peak discharges and similar or longer times to peak compared to the decentralized wetlands scenarios. For water quality, the retention based GI, which promotes infiltration and volume reductions, resulted in similar or better water quality outcomes than the decentralized wetlands for TN, TDS, and TP. However,
NO$_3^-$ loads were more efficiently removed by the decentralized wetlands scenarios. Similar to above, wetlands are particularly efficient at removing NO$_3^-$ (Table 3, Leisenring et al. 2014; Hansen et al. 2018) thus a greater load of NO$_3^-$ can be removed from the system when runoff flows through wetlands rather than infiltrating.

A second model scenario examines distributed infiltration based stormwater management. The soil management scenario keeps the percentage of impervious surfaces the same as the other scenarios, but infiltration is promoted in the pervious portions of the catchment by increasing hydraulic conductivity by a factor of 10. The time to peak for the soil management scenario was shorter than any of the other model scenarios. The impact of peak flows was comparable to the decentralized wetlands and green roof scenarios for the 1 y storm, but peaks were reduced more as the storm size increased. The soil management scenario also resulted in the greatest reduction in runoff volumes compared to all other scenarios. The impact on water quality for the 1 y storm is similar to that of the green roof scenario. But as storm size increased from the 1 y to 10 y and 100 y storms, the soil management scenario resulted in the greatest water quality improvements for all pollutants, including NO$_3^-$.

Results suggest that, in the study catchment, urban soils can impact hydrologic response and that even when opportunities to treat urban impervious areas with GI are limited, there may be similar or greater benefits gained by improving infiltration in the pervious portions of a catchment.

### 4.3 Study limitations and future work

One limitation of this study is that a single concentration was used to represent each pollutant, when in reality pollutant concentrations change over time and over the course of a single storm (Jefferson et al. 2017). As high frequency sensor data for water pollutants become more readily available (Kaushal et al. 2021), it will become more feasible to better model water quality characteristics at finer time scales. While the focus of this study was on the storm event response due to stormwater wetlands and green roofs in the Kromma Kill subwatershed, results would be kept constant, decentralized wetlands reduced flood volumes more than a large centralized one due to attenuation and dispersal of decentralized wetland outflow within the storm pipe network. And when infiltration in the pervious portion of the catchment was promoted, runoff volumes were reduced in the catchment even more than in scenarios with smaller effective impervious percentages. For water quality, while reductions in flood volumes do generally result in water quality benefits, for pollutants that are particularly efficiently removed by wetlands, such as NO$_3^-$, it was more advantageous to route runoff through a large centralized wetland rather than letting it infiltrate where it fell.

As the trend to favour distributed GI continues (Jefferson et al. 2017), it will be important for watershed managers to recognize that for multi-objective management plans, distributed GI may not be able to fully replace centralized stormwater management practices. Furthermore, while minimizing effective imperviousness my be promoted as a one-size-fits-all solution to reducing flooding and improving water quality (Meierdiercks et al. 2017), drainage network structure and infiltration in pervious portions of the catchment should also be considered.

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Appendix

Table A1  Results of SWMM water quality modeling for the 10 y design storm; negative percentage change values indicate water quality improvements.

| Model Scenario                      | TN    | TDS   | NO₃⁻ | TP   |
|-------------------------------------|-------|-------|-------|------|
| Outflow concentration (mg/L)        |       |       |       |      |
| Business as Usual (large, central wetland) | 5.17  | 434.22| 1.60  | 0.43 |
| Control (no wetland, no GI)         | 5.19  | 436.38| 3.54  | 0.64 |
| Decentralized wetlands              | 5.80  | 488.33| 3.39  | 0.63 |
| Decentralized wetlands (upstream imperviousness) | 5.33  | 448.67| 2.71  | 0.51 |
| Decentralized green roofs           | 4.10  | 342.61| 2.77  | 0.50 |
| Soil management                     | 5.28  | 447.75| 3.67  | 0.66 |
| Outflow concentration % change      |       |       |       |      |
| Business as Usual (large, central wetland) | –     | –     | –     | –    |
| Control (no wetland, no GI)         | 0.5%  | 0.5%  | 120.9%| 48.8%|
| Decentralized wetlands              | 12.4% | 12.5% | 111.0%| 48.1%|
| Decentralized wetlands (upstream imperviousness) | 3.2%  | 3.3%  | 69.1% | 19.0%|
| Decentralized green roofs           | –20.6%| –21.1%| 72.5% | 16.0%|
| Soil management                     | 2.3%  | 3.1%  | 128.8%| 54.5%|
| Outflow loading (lbs)               |       |       |       |      |
| Business as Usual (large, central wetland) | 69.3  | 5829.3| 21.5  | 5.7  |
| Control (no wetland, no GI)         | 70.5  | 5925.2| 48.1  | 8.6  |
| Decentralized wetlands              | 72.1  | 6063.1| 42.0  | 7.9  |
| Decentralized wetlands (upstream imperviousness) | 66.7  | 5614.6| 34.0  | 6.4  |
| Decentralized green roofs           | 44.2  | 3694.7| 29.8  | 5.4  |
| Soil management                     | 24.0  | 2035.5| 16.7  | 3.0  |
| Outflow loading % change            |       |       |       |      |
| Business as Usual (large, central wetland) | –     | –     | –     | –    |
| Control (no wetland, no GI)         | 1.6%  | 1.6%  | 123.4%| 50.5%|
| Decentralized wetlands              | 3.9%  | 4.0%  | 95.2% | 37.0%|
| Decentralized wetlands (upstream imperviousness) | –3.8% | –3.7% | 57.6% | 10.9%|
| Decentralized green roofs           | –36.2%| –36.6%| 38.6% | –6.8%|
| Soil management                     | –65.4%| –65.1%| –22.5%| –47.7%|

Table A2  Results of SWMM water quality modeling for the 100 y design storm; negative percentage change values indicate water quality improvements.

| Model Scenario                      | TN    | TDS   | NO₃⁻ | TP   |
|-------------------------------------|-------|-------|-------|------|
| Outflow concentration (mg/L)        |       |       |       |      |
| Business as Usual (large, central wetland) | 5.24  | 441.66| 1.69  | 0.44 |
| Control (no wetland, no GI)         | 5.28  | 445.20| 3.62  | 0.65 |
| Decentralized wetlands              | 5.84  | 487.31| 3.31  | 0.62 |
| Decentralized wetlands (upstream imperviousness) | 5.10  | 429.17| 2.75  | 0.51 |
| Decentralized green roofs           | 4.28  | 360.16| 2.92  | 0.52 |
| Soil management                     | 5.23  | 438.37| 3.58  | 0.64 |
| Outflow concentration % change      |       |       |       |      |
| Business as Usual (large, central wetland) | –     | –     | –     | –    |
| Control (no wetland, no GI)         | 0.7%  | 0.8%  | 114.7%| 46.9%|
| Decentralized wetlands              | 11.5% | 10.3% | 96.4% | 39.6%|
| Decentralized wetlands (upstream imperviousness) | –2.6% | –2.8% | 63.1% | 14.6%|
| Decentralized green roofs           | –18.2%| –18.5%| 73.1% | 18.3%|
| Soil management                     | –0.2% | –0.7% | 111.9%| 45.1%|
| Outflow loading (lbs)               |       |       |       |      |
| Business as Usual (large, central wetland) | 149.6 | 12611.6| 48.2 | 12.7 |
| Control (no wetland, no GI)         | 153.5 | 12953.0| 105.4| 19.0 |
| Decentralized wetlands              | 152.4 | 12719.8| 86.5 | 16.2 |
| Decentralized wetlands (upstream imperviousness) | 133.6 | 11246.6| 72.1 | 13.3 |
| Decentralized green roofs           | 100.3 | 8433.4| 68.4 | 12.3 |
| Soil management                     | 63.5  | 5330.2| 43.5 | 7.8  |
| Outflow loading % change            |       |       |       |      |
| Business as Usual (large, central wetland) | –     | –     | –     | –    |
| Control (no wetland, no GI)         | 2.7%  | 2.7%  | 118.8%| 49.7%|
| Decentralized wetlands              | 1.9%  | 0.9%  | 79.5% | 27.6%|
| Decentralized wetlands (upstream imperviousness) | –10.6%| –10.8%| 49.7% | 5.2% |
| Decentralized green roofs           | –32.9%| –33.1%| 41.9% | –3.0%|
| Soil management                     | –57.5%| –57.7%| –9.8% | –38.2%|