Updating the Runoff Reduction Method




Prepared For:

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INTRODUCTION

The Charge of Updating the Runoff Reduction Numbers

The original technical memorandum on the Runoff Reduction Method (RRM) was produced in 2008, accounting for stormwater control measure (SCM) research conducted through 2007 (CWP & CSN, 2008). The memorandum provided a framework for Virginia's emerging stormwater management program, and the method has since been utilized in other jurisdictions, including the City of Nashville.

At the time, the authors acknowledged the limited number of available studies, particularly for some SCM categories:

> *The biggest caveat to the data. . .is the limited number of studies available that reported BMP runoff reduction or EMC based nutrient removal efficiencies. As a result, some of the numbers listed in the tables will be subject to change as more studies and data become available. The numbers in the tables are the authors' best judgment based on currently-available information.* (CWP & CSN, 2008, p. 9).

The current project, conducted by the original authors in addition to other researchers, presents an opportunity to update the information based on research and studies conducted from 2007 through 2017. The effort was undertaken to support the City of Nashville's stormwater program and LID Manual (Metro Water Services, 2016). Nashville's stormwater standard is based on volume (runoff reduction); as a result, this report focuses on updating the runoff reduction capabilities of the SCMs included in Nashville's LID Manual.

Table 1 notes the number of studies per practice contained in the original RRM memo compared to new studies analyzed for this project. As can be seen from the table, some practices were represented more heavily than others. Bioretention and Permeable Pavement are the favored topics of newer research. Some of the same practices that were under-represented in the original analysis still contain a limited number of studies (e.g., extended detention, grass channels). In addition, some newer categories, such as Urban Bioretention, are not currently supported by an abundance of research on runoff reduction (and the term is not used universally to describe the same practice). Given those limitations, newer studies do provide a more robust body of data to support professional application. The exercise of updating the research findings should be conducted on a periodic basis, as the field of stormwater research continues to expand at universities and research agencies.

Table 1. Comparison of Studies in the Runoff Reduction Technical Memo (2008) to those Collected for the Current Project		
SCM & Nashville LID Manual Chapter Reference	**Original RRM Memo: through 2007 (CWP & CSN, 2008, Appendix B)**	**New Studies: 2007 – 2016[1]**
Bioretention (GIP-01)	11	39
Urban Bioretention (GIP-02)	1	3
Permeable Pavement (GIP-03)	14	16
Infiltration (GIP-04)	4	8
Water Quality Swale (GIP-05)	3	1
Extended Detention Pond (GIP-06)	5	6
Grass Channel (GIP-08)	4	10
Sheet Flow (GIP-09)	5	8
Green Roof (GIP-12)	9	13
[1] These numbers represent the number of studies collected and reviewed for this project. Not every study reported runoff or volume reductions. In addition, many papers studied multiple practices, so the actual number of SCMs monitored for runoff reduction is higher than the number of papers. The practice-specific sections of this report provide more information on these variables.		

Recommendations From This Study

Table 2 summarizes the recommendations of this project based on a review of the studies. The following sections present a more detailed analysis for each SCM type.

Table 2. Summary of Recommendations for Runoff Reduction Rates	
SCM	**Summary of Recommendations**
Bioretention (GIP-01)	• Increase Level 1 rate from 40 to 60% • Keep Level 2 rate at 80% • Add alternative Level 2 with internal water storage (IWS)
Urban Bioretention (GIP-02)	• Not enough new data for change
Permeable Pavement (GIP-03)	• Decrease Level 1 from 45 to 30% • Increase Level 2 from 75 to 80% • Clarify IWS as Level 2 option with minimum measured infiltration rate
Infiltration (GIP-04)	• Maintain existing sizing and infiltration testing criteria
Water Quality Swale (GIP-05)	• Not enough new data for change
Extended Detention Pond (GIP-06)	• Increase unlined ED ponds from 15 to 25%, with possible inclusion of soil analysis
Grass Channel (GIP-08)	• Not enough new data for change to RR rate • Consider adding vegetated check dams
Sheet Flow (GIP-09)	• Adjust lower end of rate to 40% and allow rate increases for longer filter lengths
Green Roof (GIP-12)	• Adjust Level 1 to 10% times media depth, with minimum depth of 3 inches • Adjust Level 2 to 12% times media depth, with minimum depth of 4 inches • Maximum runoff reduction for both levels = 90%

What Do The Numbers Mean?

The purpose of this study is to support Nashville's stormwater compliance program. As such, the runoff reduction rates need to be based on solid technical and scientific resources, and provide a logical link to the specifications in the LID Manual. With this as a guiding principle, it must be acknowledged that there is no standardization in how researchers measure and report volume or runoff reduction data. Some base the calculation on the total volume of runoff entering and leaving a practice during the entire study period. Others measure volume reduction for numerous individual storm events, and then average the results. Some studies aim to measure and model the mechanisms of evaporation, transpiration, exfiltration, underdrain flow, and overflow. Yet others compare "treatment" sites with control sites.

It would be a daunting task, indeed, to attempt to standardize or normalize these data sets. The approach taken, therefore, was to review the papers carefully, understand what was being measured, and rely on a weight of evidence approach to discern convergences of the data towards certain values. In some cases, hand calculations were performed based on raw data presented in the papers to derive comparable runoff reduction rates. Typical of SCM monitoring, there was a lot of "scatter" in some data sets. Variability is likely due to design factors, the size and intensity of monitored storms, drainage areas, monitoring methods, age of SCM and degree of maintenance, and other factors. Once study results and associated SCMs were categorized as Level 1 or 2 design, the variability declined.

The fact that this type of analysis is not perfect should be understood in the context of supporting compliance. Both the design community preparing plans for review and the plan reviewers need a predictable and supportable number so that each site plan can be treated on a consistent scale, and the practices used (if properly constructed and maintained) have a strong likelihood of performing at a certain level. That said, the data can and should be updated on a periodic basis, as new studies are ongoing, with many having a stronger focus on measuring volume.

Methodology

The methodology for the project included, in general terms, the following steps:

- Team members collected newer research studies based on professional contacts and recent work. The team was assembled based on their knowledge of this type of research. All papers were collected into a shared folder and categorized by practice. A spreadsheet was developed to collect runoff reduction data in a systematic way.
- Dr. Hathaway from the University of Tennessee and his graduate students reviewed all of the collected studies and added some of their own. The students entered data into the spreadsheet, documenting study variables, runoff reduction rates, methods of analysis, number of storms sampled, and other data. Brief study descriptions were also added.
- Subsequently, the other team members conducted thorough reviews of the data. This included, to the extent possible, categorizing individual practice studies as Level 1 or 2 based on the standards in Nashville's LID Manual. The data were analyzed for basic statistics, such as mean and median runoff reduction rates. In some cases, outliers were either included or excluded based on the circumstances depicted in the studies.

- Team members also distilled SCM design take-home points and recommendations for each practice. The team decided that specific recommendations would not be derived in cases where there were fewer than 5 studies in a SCM category.
- Throughout the process, the team held conference calls to discuss methodology, issues that arose with comparing data that were collected using different methods, and appropriate recommendations.
- Team members reviewed the final analysis and recommendations.

The Study Team

The current study team included the following individuals and organizations:

- David J. Hirschman, Principal, Hirschman Water & Environment, LLC (team lead)
- Dr. Jon Hathaway, PE, PhD, University of Tennessee, Department of Civil & Environmental Engineering; Graduate Students: Jessica Thompson, Whitney Lisenbee, Padmini Persaud, Andrew Tirpak
- Kelly Collins Lindow, PE, Principal and Founder*,* CityScape Engineering, LLC
- Tom Schueler, Chesapeake Stormwater Network
- Dr. Marcus Aguilar, formerly Virginia Tech

Remaining Sections of This Report

The following sections provide more detailed analyses of the updated research, organized as the SCMs are listed in the Nashville LID Manual. Note that some sections contain more content than others based on the number of studies that were reviewed and the degree to which recommendations were distilled from the research.

Also, not every practice in the current LID Manual is included. The following SCMs are not included in this analysis based on proposed content for the updated Manual, or the fact that runoff reduction rates are design dependent or involve factors beyond the scope of this study:

- Downspout Disconnection (GIP-07)
- Reforestation (GIP-10)
- Cistern (GIP-11)

BIORETENTION (GIP-01)

Table 3. Summary of Updated Study	
New Studies Reviewed: 2007 -- 2016	39
# Reporting Runoff Reduction Rates	20
# of Individual Practice Runoff Reduction Rates Measured (counting multiple practices for some studies)	35

Table 4. Summary of Updated Research With Existing Runoff Reduction Rates

	Level 1	**Level 2**	**Alternative: Internal Water Storage (IWS)**
# of practices studied	12	13	10
Mean Runoff Reduction	59%	80%	77%
Median Runoff Reduction	63%	89%	87%
Existing Nashville LID Rate	40%	80%	N/A
Proposed Rate	60%	80%	80% (alternative Level 2)

Design Factors: Take-Home Points

- Not surprisingly, practice size, storage, and media depth are important factors for runoff reduction. The research supports enhanced runoff reduction rates for increased overall size and media depth of around 3 feet. These practices also contribute to reducing peak flows and extending the time to peak (Davis et al., 2012; Brown & Hunt, 2011b; Li et al., 2009; Selbig & Balster, 2010).
- The inclusion of an Internal Water Storage (IWS) zone (upturned elbow) appears to enhance runoff reduction on an average annual basis. While the IWS can take up some storage, especially during high intensity events, it also promotes enhanced exfiltration through the sides of the practice, as the water within the IWS remains in the practice for longer periods of time. IWS seems to work best in soils that are somewhat limited for infiltration (e.g., more on the clayey side). In sandier soils, there is not enough residence time within the IWS for the modification to affect runoff reduction performance. IWS also enhanced removal of dissolved forms of Nitrogen (Brown & Hunt, 2011a; Li et al., 2009; Winston et al., 2016; see also discussion of IWS in Hirschman et al., 2017).
- The type of vegetation does matter. Deeper rooted vegetation extending down into the soil media layer and dense underground biomass retains more moisture compared to shallower root systems, such as turf grass (Selbig & Balster, 2010; see also discussion of vegetation in Hirschman et al., 2017).
- There is some support in the research for continued use of low organic matter, permeable soils (Davis et al., 2012). However, there is a countervailing argument that the practices are "over-drained," reducing residence time and processing of pollutants. Some researchers indicate that

existing infiltration testing standards are too restrictive, and that infiltration/exfiltration plus evapotranspiration will account for large percentages of runoff reduction, provided the practices are adequately sized or oversized for the drainage area (Selbig & Balster, 2010; Wadzuk et al., 2017).

- From a runoff reduction perspective, avoid excavated cells that intercept groundwater (Line & Hunt, 2009).
- Pre-treatment, as intended, can increase the life of a practice and decrease maintenance burden (Lewellyn et al., 2016).

Recommendations

- Consider elevating Level 1 RR rate to 60%
- All infiltration designs qualify for Level 2, given adequate infiltration testing. Reduced media depth (e.g., 30") may be justified for confirmed infiltration designs.
- Maintain treatment volume (Tv) sizing criteria and media depth specifications (with possible revisions for IWS as explained below).
- Add IWS as a Level 2 option, or replace existing stone sump with IWS. There may be some support for reducing the media depth if IWS is used (e.g., 30"), but this needs some additional analysis. Also, the depth of the IWS zone and whether the zone should intercept the soil media layer needs further analysis. If the media layer is intercepted, then it is recommended to leave at least the top 18" of media in an unsaturated condition. Further analysis of IWS specifications is taking place in a separate study being undertaken by some of the authors.
- Consider revising planting plan specifications, allowing for a densely-planted, native meadow that can be cut back annually in the early Spring. This may provide a more maintenance-friendly landscape. Trees can certainly be incorporated into some designs, and can be an option as long as the maintenance tasks are understood by the responsible party.

Table 5. Bioretention Studies Arranged by Design Level [1]	
LEVEL 1 Runoff Reduction	
Brown & Hunt, 2011b	63%
Brown & Hunt, 2012	88%
Davis et al., 2012	77%
Hatt et al., 2009	11%, 30%, 33%
Hunt et al., 2008	99%
Jarden et al., 2016	40%
Li et al., 2009	40%, 77%, 89%
Line & Hunt, 2009	-9%[2]
Mean/Median	**59%/63%**
LEVEL 2 Runoff Reduction	
Brown & Hunt, 2011b	65%
Brown & Hunt, 2012	89%
Davis et al., 2012	52%
Jarden et al., 2016	36%
Komlos & Traver, 2012	47%, 90%, 90%
Selbig & Balster, 2010	100%, 98%, 98%, 95%

Wadzuk et al., 2017	89%
Xiao and McPherson, 2011	89%
Mean/Median	**80%/89%**
INTERNAL WATER STORAGE	
Brown & Hunt, 2011a	100%, 98%, 75%, 87%
Davis et al., 2012	86%, 90%
Winston et al., 2016	59%, 42%, 36%
DeBusk & Wynn, 2011	97%
Mean/Median	**77%/87%**
[1] Rows with multiple values indicate that the study included multiple practices with different design features.	
[2] This value was considered an outlier and not counted in the mean/median values. The study had some issues with measurement of outflow and the practice intercepted the water table.	

URBAN BIORETENTION (GIP-02)

There were only 3 studies that were classified as Urban Bioretention. Some of this may have been due to nomenclature in that the various practices categorized under regular Bioretention (GIP-01) included different configurations, but most were typical applications, treating parking lots, rooftops, streets, etc.

Of the 3 classified as Urban Bioretention, only one reported volume reductions (Geronimo et al., 2014) with the reported value of 40%, matching the existing runoff reduction rate. Additional Urban Bioretention systems were studied in conjunction with other practices as part of treatment trains, but runoff reduction rates were reported for the entire treatment train rather than its individual components (Brown et al., 2013; Line et al., 2012; Page et al., 2015; Wilson et al., 2015).

Due to the lack of additional data points, there is insufficient information at this point to modify the existing runoff reduction rate.

PERMEABLE PAVEMENT (GIP-03)

Table 6. Summary of Updated Studies	
New Studies Reviewed: 2007 - 2016	16
# Reporting Runoff Reduction Rates	10
# of Individual Practice Runoff Reduction Rates Measured (counting multiple practices for some studies)	19

Table 7. Summary of Updated Research With Existing Runoff Reduction Rates		
	Level 1	**Level 2**
# of practices studied	13	6
Mean Runoff Reduction	35	96
Median Runoff Reduction	32	99
Existing Nashville LID Rate	45	75
Proposed Rate	30	80

Design Factors: Take-Home Points

- Studies show very little surface runoff from maintained permeable pavements. Consequently, practices in well drained soils (HSG A and B) with adequate storage and no underdrain yield very high runoff reduction results.
- In HSG C and D soils, the inclusion of an Internal Water Storage (IWS) zone can enhance runoff reduction by promoting slow infiltration (Collins et al, 2008; Wardynski et al, 2013; Winston et al, 2015). Significant results were noted for IWS depths of 6 inches or greater and when the underlying soil infiltration rate was greater than 0.01 in/hr.
- Ripping or trenching of the subgrade can help improve infiltration rates in HSG C or D soils (Tyner et al, 2009; Wardynski et al, 2013)
- Increasing the contributing drainage area or hydraulic loading ratio to the permeable pavement surface area beyond 3:1 decreased runoff reduction performance (Winston et al, 2015; Smolek and Hunt, 2015).

Recommendations (based on existing Section 3 Design Table)

- Consider lowering Level 1 RR rate from 45% to 30%.
- Consider raising Level 2 RR rate from 75% to 80%.
- For Level 2, consider modifying the Section 6 Design Criteria:
    - Set a predicted drawdown (infiltration) of captured runoff (e.g. 24 to 48 hours) based on infiltration testing.
    - Modify and clarify the Internal Water Storage (IWS) criteria (e.g., minimum 6” IWS in HSG C/D soils, with measured infiltration > 0.1 inches/hour). The current specification allows either a sump below the underdrain OR IWS. Both may be valid options. The chief advantage of IWS in this application might be enhanced runoff reduction due to increased exfiltration out the sides and bottom.

- Maintain limits on hydraulic loading (off-site run-on onto the permeable pavement).

Table 8. Permeable Pavement Studies Arranged by Design Level[1]

LEVEL 1 Runoff Reduction	
Collins et al., 2008	19.2%
Collins et al., 2008	39.3%
Collins et al., 2008	31.8%
Collins et al., 2008	6.7%
Dreelin et al, 2006	73%[2]
Fassman and Blackbourn, 2010	28%
Smolek and Hunt, 2015	22%
Drake et al, 2012	43%
Wardynski et al, 2013	78%
Crookes et al, 2017	46%
Winston et al, 2015	16%, 32%, 53%
Winston et al, 2015	16%
Winston et al, 2015	32%
Mean/Median	**35%/32%[3]**
LEVEL 2 Runoff Reduction	
Bean et al, 2007	100%
Bean et al, 2007	89.9%
Bean et al, 2007	87.6%
Winston et al, 2015	99%[4]
Wardynski et al, 2013	100%[4]
Wardynski et al, 2013	99.6%[4]
Mean/Median	**96%/99%**

[1] Rows with multiple values indicate that the study included multiple practices with different design features.
[2] This value was considered an outlier and not counted in the mean/median values. The study looked at selected small intensity events, excluding larger events.
[3] The mean/median = 27% when permeable pavement was compared to a control asphalt area, which may be a more realistic way to measure actual runoff reduction.
[4] Design included Internal Water Storage (IWS).

INFILTRATION (GIP-04)

Table 9. Summary of Updated Study	
New Studies Reviewed: 2007 – 2016[1]	8
# Reporting Runoff Reduction Rates	3
# of Individual Practice Runoff Reduction Rates Measured (counting multiple practices for some studies)	3
[1] Three of these studies were included in the Original RRM, but storm event data became available since its completion.	

Table 10. Summary of Updated Research With Existing Runoff Reduction Rates		
	Level 1	**Level 2**
# of studies practices	3	
Mean Runoff Reduction	92%	
Median Runoff Reduction	93%	
Existing Nashville LID Rate	50%	90%

Design Factors: Take-Home Points

The volume reduction performance of infiltration SCMs depends on the size of the practice with respect to the contributing drainage area, and the infiltrative capacity of the native soils surrounding the SCM. Facilities sized for as small as the one-half inch of rainfall may still have performance in the 90% range, although the native soil infiltration capacity will affect the level of this performance. It should be noted that the studies reviewed all had reasonable or favorable infiltration rates in native soils.

Recommendations

- Infiltration facilities can provide high levels of runoff reduction, even if the facility is sized for a relatively small storm event. For example, the bioinfiltration facility in Wadzuk et al. (2017) was sized to capture the first 0.5” of runoff from the impervious surfaces in the contributing drainage area. While the facility successfully captured 100% of runoff from events less than or equal to 0.5”, it also captured 97% of volume from storms between 0.5” and 1.0”, and 50% from all larger events. Likewise, the infiltration trench in Lewellyn et al. (2016) was sized to capture the 1.0” event, but has consistently prevented any surface outflow for much larger storms. Therefore the 1.0” and 1.1” criteria for rainfall depth capture that is currently used for L1 and L2 sizing (respectively) is likely to be sufficient.
- One note of interest is the emphasis in Wadzuk et al. (2017) that a properly designed infiltration facility needs little to no maintenance. This is anecdotal evidence after 13 years of monitoring a single infiltration SCM, and there are likely to be exceptions to this – especially at sites that generate excessive solids in their runoff.
- Reported saturated hydraulic conductivity of native soils in studies reviewed was 0.23 in/hr. (Horst et al. 2011) and 5.8 in/hr. (Lewellyn et al. 2016) [not reported in Wadzuk et al. (2017)]. This suggests that a broad range of existing soil infiltration capacity can provide substantial volume reduction benefits.

Table 11. Infiltration Studies and Mean Runoff Reduction Rates		
Reference	**Mean %RR**	**Notes**
Wadzuk et al. (2017)	Events w. > ¼ in. rainfall = 54.2% Events w. 0.05 in < P < 1.6 in. = 89%	Thirteen years of monitoring data
Horst et al. (2011)	93%	Three linked infiltration beds overlaid with geotextile filter fabric and coarse aggregate, sized to store the first 2.0" of rainfall
Lewellyn et al. (2016)	93%	Infiltration trench with vegetated side slopes for pretreatment

WATER QUALITY SWALE (GIP-05)

The one new study included in the Water Quality Swale category had wetland swale characteristics and did not report volume reductions (Winston et al., 2012). An additional study (Xiao and McPherson, 2011) identified the studied practice as a "bioswale," but examination of the paper indicated that it was more similar to typical bioretention, so it was moved to the GIP-01 category.

Due to the lack of additional data points, there is insufficient information at this point to modify the existing runoff reduction rate.

EXTENDED DETENTION (GIP-06)

Table 12. Summary of Updated Study	
New Studies Reviewed: 2007 – 2016[1]	6
# Reporting Runoff Reduction Rates	5
# of Individual Practice Runoff Reduction Rates Measured (counting multiple practices for some studies)	7
[1]These were not new studies *per se*, but older studies where the storm event data became available after the Original RRM report in 2007.	

Table 13. Summary of Updated Research With Existing Runoff Reduction Rates		
	Lined	**Design Specified (Unlined)**
# of studies practices	0	7
Mean Runoff Reduction	N/A	34%
Median Runoff Reduction	N/A	25%
Existing Nashville LID Rate	0%	15%

Design Factors: Take-Home Points

In principle, the design factors that would provide for increased runoff volume reduction in extended detention (ED) ponds are: (1) increased pond surface area providing higher evaporation potential, (2) increased hydraulic residence time or drawdown time providing higher evaporation potential, (3) infiltration capacity of native soils and (4) transpiration by emergent vegetation. However, as ED pond monitoring studies typically do not focus on runoff volume reduction, it was not possible to substantiate these logical hydrologic pathways with empirical data.

Recommendations

There are limited empirical monitoring studies that focus on the volume reduction benefits of ED ponds, as most studies focus on the capture of sediment and associated constituents. Nevertheless, several of these studies record volume reduction as an ancillary part of the monitoring program, and have reported these data to the International Stormwater BMP Database. In an analysis of the available data as of 2011, Geosyntec Consultants and Wright Water Engineers calculated the total volume reduction of each individual study, then calculated the median of all studies as 33%. This is similar to the results of an earlier analysis by Strecker (2004) – average %RR = 30% - included in the initial RRM. The data from this report were reviewed, and the results shown in Table 14. It should be noted that all of the ED ponds shown in the Table are grass lined ponds, as there was insufficient data to perform any meaningful analysis on the lined ED ponds.

Rather than lump the total volume of each individual study, and then calculate summary statistics, summary statistics were calculated using each individual storm event (n = 84) from the seven sites shown in Table 14. Summary statistics were as follows: 1st quartile = 13%; Median = 25%, 2nd quartile (Mean) = 33%, 3rd quartile = 51%.

Table 14. Results of Extended Detention (ED) pond monitoring studies as median percent runoff reduction (%RR) for all storm events monitored		
Source Study Reference	**Site**	**Median %RR**
Huber et al., 2006; Liptan, 2001	Lexington Hills	67
Hussain et al., 2005	Carver County	50
Yu et al., 1994	Massie Road	37
CALTRANS, 2004	I-5/Manchester	37
CALTRANS, 2004	I-5/SR-56	24
CALTRANS, 2004	I-5/SR-78	18
Stanley, 1996	Greenville Pond, NC	7

Based on the results shown in Table 14, as well as the findings of the Original RRM study, %RR credit for unlined ED ponds (i.e. "Design Specified") could reasonably be increased from the current 15% to 25%. Perhaps the higher rate could be tied to a soils analysis and/or adding soil amendments to the bottom of the pond. There is no new empirical evidence to suggest that lined EDs provide a volume reduction benefit that is significantly greater than zero.

GRASS CHANNEL (GIP-08)

Table 15. Summary of Updated Study	
New Studies Reviewed: 2007 – 2016[1]	10
# Reporting Runoff Reduction Rates	3
# of Individual Practice Runoff Reduction Rates Measured (counting multiple practices for some studies)	6
[1]Three of these studies were included in the Original RRM, but storm event data became available since its completion.	

Table 16. Summary of Updated Research With Existing Runoff Reduction Rates		
	Without Compost Amendments	**With Compost Amendments**
# of studies practices	6	0
Mean Runoff Reduction	37%	N/A
Median Runoff Reduction	81%	N/A
Existing Nashville LID Rate[1]	10 – 20%	20 – 30%
[1]Level 1 = HSG Soils C and D. Level 2 = HSG Soils A and B. Ranges of RR for each Level are for no compost amendment (low end) vs. compost amendment (high end).		

Design Factors: Take-Home Points

The literature on key factors affecting hydrologic function of grass channels has not substantially grown since the Original RRM. The two key points from this review are that (1) Grass Channels may provide a higher level of runoff reduction than initially expected and (2) the use of check dams comprised of sturdy vegetation (e.g. *Panicum virgatum*) can increase volume reduction during moderate rainfall events. These two findings are attributable to Davis et al. (2012), as the other two studies reviewed were limited in their analysis of hydrologic outcomes.

Recommendations

- Consider the use of in-line vegetated check dams, as these led to significantly improved volume reduction for storm events between 1 – 1.3 in. depth in Davis et al. (2012). For example, the volume reduction in the MD Department of Environment (MDE) swale in this study increased from a median of 10% across all storm events to a median of 100% after check dams were installed.
- Pre-treatment filter strips appeared to have a minimal effect on performance (Davis et al. 2012), and as a result it is recommended that these be incorporated into the Manual as a possible alternative, but not as a requirement for increased credit.

Table 17. Grass Channel Research & Median Runoff Reduction Rates

Reference	Median %RR	Notes
Davis et al. (2012)	11%, 64%, 89%, 100%	Evaluated the effects of pre-treatment filter strips and check dams
Knight et al. (2013)	23%	Compared swale performance to VFS performance
Lucke et al. (2014)	52%	Not focused on volume reduction

SHEET FLOW (GIP-09)

Table 18. Summary of Updated Study

New Studies Reviewed: 2007 – 2016[1]	8
# Reporting Runoff Reduction Rates	6
# of Individual Practice Runoff Reduction Rates Measured (counting multiple practices for some studies)	38

[1] Three of these studies were included in the Original RRM, but storm event data became available since its completion.

Table 19. Summary of Updated Research With Existing Runoff Reduction Rates

	Sheet Flow to Conservation Area	Sheet Flow to Vegetated Filter Strip
# of studies/practices	0	38
Mean Runoff Reduction	N/A	43%
Median Runoff Reduction	N/A	40%
Existing Nashville LID Rate	50%/75% in HSG A/B & C/D respectively	50%

Design Factors: Take-Home Points

In theory, there are several design factors that would lead to increased runoff volume reduction using sheet flow, including the conservation area or filter strip's (1) length, (2) slope, (3) vegetation, (4) soil infiltration; and (5) the extent to which flow is diffused prior to entering the conservation area or filter strip. Overall, the literature confirms that filters of increased length provide higher volume reduction (e.g. Hunt et al., 2010, Abu-Zreig et al., 2004), though the relationship does not follow a clear pattern. The effect of slope is less visible as some filters with extremely high slopes had relatively high volume reduction. For example, the San Rafael Roadside Vegetated Treatment System (CALTRANS, 2003) had a slope of 50%, but provided a median volume reduction over 34 storm events of 65%. Inversely, the Altadena Strip (CALTRANS, 2004) had a milder slope of 3%, but only provided 10% median volume reduction over 12 storm events.

It was not possible to draw any conclusions about the effect of vegetation type, as all the studies reviewed used some type of grass, though Blanco-Canqui et al. (2004) note that the installation of a switchgrass barrier perpendicular to flow increased detention time and infiltration. The only study that evaluated the effects of soil amendments and flow diffusion was Knight et al. (2013). The results of this study indicate that while a wider filter (measured in the direction perpendicular to flow) increases volume reduction, the soil amendments did not have a significant effect.

Recommendations

- In general, the lumped value of 50% credit given for vegetated filter strip (VFS) is slightly higher than the central values from the literature (mean = 43%, median = 40%), though not as high as the third quartile value of 75%. As the literature indicates that volume reduction is a function of slope length, the City may consider lowering the baseline credit given for the use of a VFS to 40%, and increasing credit with slope length to incentivize longer lengths of sheet flow.
- The City may also consider the findings of a similar review by Battiata et al. (2014), indicating that the loading ratio – the drainage area divided by the area of the filter strip - appeared to affect runoff reduction across studies reviewed.
- None of the literature reviewed reasonably met the criteria for Conserved Open Space, and as a result no recommendations are given for this variety of the practice.

Table 20. Sheet Flow Research & Median Runoff Reduction Rates

Reference	Median %RR	Notes
Abu-Zreig et al. (2004)	25, 25, 41, 42, 44, 58, 63%	Evaluated effect of slope and length
Blanco-Canqui et al. (2004)	2.2, 5.4, 5.6,11, 13, 13, 18, 20, 20, 20, 21, 28%	Evaluated effect of vegetation and length
CALTRANS (2003)	0, 12, 14,26,37,40, 52, 60,63, 64, 70%	Evaluated effect of slope and length
CALTRANS (2004)	10, 45, 92%	
Hunt et al. (2010)	100%	
Knight et al. (2013)	36, 42, 57, 59%	Evaluated effect of width and soil amendments

GREEN ROOF (GIP-12)

Table 21. Summary of Updated Studies	
New Studies Reviewed: 2007 - 2016	10
# Reporting Runoff Reduction Rates	11
# of Individual Practice Runoff Reduction Rates Measured (counting multiple practices for some studies)	23

Table 22. Summary of Updated Research With Existing Runoff Reduction Rates		
	Level 1	**Level 2**
# of practices studied	18	5
Mean Runoff Reduction[1]	62	61
Median Runoff Reduction[1]	67	69
Existing Nashville LID Rate	45	60
Proposed Rate	Credit based on thickness (0.1 x thickness)	Credit based on thickness (0.12 x thickness) with max credit of 90%
[1] The majority of reported runoff reduction rates were measured during summer months only. Further, many studies were sample plots not indicative of actual green roof conditions. Refer to discussion below about design factors and recommendations.		

Design Factors: Take-Home Points

- Green roof performance varies by season. During warm summer months, significantly more evapotranspiration occurs from the green roof surface than during winter months (Hutchinson et al, 2003; Wadzuk et al, 2013).
- Vegetation increases runoff reduction rates by 7-10% compared to unvegetated roofs (media or gravel only). These results emphasize the importance of establishing healthy plant coverage on green roofs (Van Woert et al, 2005; Lang et al, 2010).
- In certain climates, vegetation may require supplemental irrigation during summer months to thrive. In a study performed by Hill et al (2017), sensor controlled or non-irrigated systems had less runoff than standard irrigation systems.
- Runoff volumes increase with increasing roof slope, resulting in lower runoff reduction values (Van Woert et al, 2005; Getter et al, 2007; Hathaway et al, 2008).
- Thicker media depths demonstrate higher runoff reduction values (Van Woert et al, 2005; Getter et al, 2007; Hathaway et al, 2008).

Recommendations

- Consider changing Level 1 RR rate to 10% times the media depth (in inches) with a minimum depth of 3 inches (30% RR) and maximum RR = 90%.
- Consider changing Level 2 RR rate to 12% times the media depth with a minimum depth of 4 inches (48% RR) and maximum RR = 90%.

- For Level 2, consider modifying the Section 6 Design Criteria:
    - Reduce minimum media depth requirement from 6 inches to 4 inches
    - No irrigation or irrigation must be controlled by sensors so that irrigation takes place based on soil moisture
    - Roof slopes 2% or flatter
    - Remove limits on hydraulic loading since green roofs typically don't receive additional runoff.
- For Level 1, consider modifying the Section 6 Design Criteria:
    - Reduce media depth requirement from 4-6 inches to minimum of 3 inches
    - Can be irrigated
    - Roof slopes 8.33% (1:12) or lower
    - Remove limits on hydraulic loading since green roofs typically don't receive additional runoff.

Table 23. Green Roof Studies Arranged by Design Level

LEVEL 1 Runoff Reduction	
Hathaway et al, 2008	77%[2]
Hathaway et al, 2008	88%[2]
Zaremba et al, 2016	78%[2]
Zaremba et al, 2016	50%[2]
Hill et al, 2017	50%[2]
Hill et al, 2017	70%[2]
Van Woert at al, 2005	69. 8%[2]
Van Woert at al, 2005	70.7%[2]
Van Woert at al, 2005	65.9%[2]
Van Woert at al, 2005	68.1%[2]
Van Woert at al, 2005	27.2%[2]
Van Woert at al, 2005	50.4%[2]
Van Woert at al, 2005	60.6%[2]
Banting et al, 2005[1]	54%
Lipton and Strecker, 2003[1]	28%
Getter et al, 2007[1]	76.4%[2]
Getter et al, 2007[1]	85.6%[2]
Denardo et al, 2005[1]	45%[2]
Mean/Median	**62%/67%**[3]
LEVEL 2 Runoff Reduction	
Lang et al, 2010	72%[2]
Lang et al, 2010	44%[2]
Hill et al, 2017	50%[2]
Hill et al, 2017	70%[2]
Hutchinson et al, 2003[1]	92%[2], 59%[3], 69%
Mean/Median	**61%/69%**[3]

[1]Study included in original RRM. [2]Runoff reduction rates measured during summer months only. [3]Runoff reduction rates measured during winter months only. Only three studies looked at annual performance and documented a significant decline in performance during winter months. [4]Mean and median not representative of annual runoff reduction rates.

TREATMENT TRAINS

Several of the research studies addressed the aggregate performance of different types of SCM's in series, or treatment trains. While not a stand-along practice, it is interesting to explore how treatment trains can be used to utilize multiple SCM runoff reduction and pollutant removal mechanisms. Table 24 provides a summary of the treatment train studies.

Table 24. Research on Treatment Trains and Retrofits

Reference	**Practices used in Treatment Train and/or Retrofit**	**Summary of Results**
Brown et al., 2012	Pervious concrete, bioretention	Total outflow volume reduced by 69%
Hathaway & Hunt, 2010	3 stormwater wetland in series	Reduced treatment after 1^{st} in series
Line et al., 2012	Bioretention, pervious concrete, constructed wetland	Reduced export of most pollutants compared to sites with no treatment or wet pond
Page et al., 2015	Bioretention, street retrofit, permeable pavement, tree filters	Runoff depth decreased by 52% compared to control catchment
Wilson et al., 2015	Green & grey: Infiltration, cisterns, swales, bioretention, underground detention	Runoff coefficient = 0.02 compared to 0.49 at conventional site with dry detention pond. LID pollutant loading were 5% of conventional site.

Design Factors: Take-Home Points

- Treatment trains using a range of practices and treatment mechanisms reduced volumes, peak rates, and pollutant loads compared to conventional practices or pre-retrofit conditions.
- Benefits were reduced when the same practice was used in series (e.g., constructed wetlands).
- Some studies are unique because they measured results from a whole site or urban catchment versus just one practice drainage area.

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