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Subject: Evaluation of Percent Imperviousness for Stormwater Control Measures (SCMs)

INTRODUCTION

This memorandum presents a literature review and evaluation of existing research and data about percent imperviousness values for different stormwater control measures to support future updates to the Runoff Chapter (Volume 1, Chapter 6) in the Urban Storm Drainage Criteria Manual (USDCM), specifically those future updates for recommended imperviousness values by surface types. As part of our ongoing research efforts to enhance stormwater management design and update regional stormwater design criteria, it is important to review and evaluate the percent imperviousness values associated with various stormwater control measures (SCMs). In urban and developed areas, impervious surfaces such as roads, parking lots, and rooftops significantly alter the natural hydrological cycle, increasing stormwater runoff and creating environmental challenges like erosion, pollution, and flooding. Understanding and effectively managing runoff from developed surfaces is fundamental for mitigating these adverse impacts and promoting sustainable stormwater management practices.

Expanding on previous work done by Wright Water Engineers (WWE) and as part of the Runoff Chapter update, the literature review in this memorandum is specific to SCMs, including but not limited to green infrastructure practices such as bioretention systems, sand filters, permeable pavement systems, green roofs, and traditional stormwater infrastructure solutions like detention basins and stormwater ponds. This evaluation considered the reliability and applicability of percent imperviousness values reported in the literature, factors such as study methodologies, geographic variability, and long-term performance data. This memorandum serves as a design basis for advancing our understanding of percent imperviousness and its relationship to SCMs. Recommended values for the different types of SCMs are presented in the conclusion of this memorandum.

METHODS

A systematic review of available literature was conducted across multiple databases, including Web of Science and Google Scholar, academic journal articles, conference papers, and technical reports/memorandums. Where research was not available, published criteria from other agencies and organizations across the United States were also considered. Each type of SCM term listed in the USDCM, Volume 3 was selected and reviewed in the relevant literature. Common search terms used in the literature review included the specific type of stormwater facility, in combination with percent imperviousness, runoff coefficients, runoff reduction, and/or volumetric runoff coefficients. These values are often used interchangeably; however, they are not always applied in the same way and can lead to different approaches for imperviousness and runoff coefficient calculations. Additional background evidence from regional research and investigations, as well as field observations at MHFD stormwater monitoring and research sites also informed recommended values.

SOURCES AND DISCUSSION FOR DETERMINATION OF IMPERVIOUSNESS VALUES

This section summarizes the literature review and supporting research related to percent imperviousness for each type of SCM.

Retention Ponds & Constructed Wetland Ponds

Retention ponds and constructed wetland ponds are considered water surfaces. A value of 100% has often been used in the region for water bodies such as lakes, reservoirs, and irrigation ponds. This is also consistent with the recommendation in a technical memorandum for water-wise landscapes (Wright Water Engineers, 2003). Because retention ponds and constructed wetland ponds have a large permanent pool, we recommend using 100% for these SCMs as well.

Rooftop Systems – Blue Roofs and Green Roofs

There are three primary types of roofs discussed in this memorandum – conventional roofs, blue roofs, and green roofs, with blue roofs and green roofs being classified as types of SCMs. Each type of roof system is briefly described below:

- Conventional roofs are commonly found in residential and commercial buildings. They are typically flat or sloped and constructed with materials like asphalt shingles, tiles, or metal panels. While they serve the primary function of providing protection from the elements, conventional roofs lack features to manage stormwater runoff as they are impervious surfaces. Rainwater typically runs off these roofs and increases runoff during storm events compared to undeveloped conditions.
- Blue roofs are a rooftop system and SCM designed to manage stormwater runoff. Unlike conventional roofs, blue roofs incorporate features to collect, store, and slowly release stormwater before discharging offsite. This controlled release helps to slow down runoff and reduce the peak flow rate during heavy rainfall events. Blue roofs, in theory, function like detention basins; however, they are not designed to receive runoff from adjacent areas.
- Green roofs, also known as living roofs or vegetated roofs, are designed to incorporate vegetation and planting systems on the rooftop system. They provide a range of environmental benefits, including stormwater management, improved air quality, energy efficiency, and enhanced biodiversity by incorporating nature-based solutions into built environments. Pertaining to stormwater, green roofs promote the retention of rainwater and reduce runoff through storage of rainwater in the media and via evapotranspiration. Green roofs are often classified into two types: extensive (with shallow soil and vegetation that doesn't require deeper soils), and intensive (with deeper soil and sometimes a wider variety of plants, potentially including trees and shrubs).

Per recommendations in a technical memorandum prepared by Wright Water Engineers (2023), the USDCM Runoff chapter published in March 2024, lists an impervious value of 95% for conventional roofs.

Key findings from the literature review conducted for blue roofs and green roofs are summarized below:

- Soulis et. al (2017) evaluated the relationship between runoff reduction for different shallow green roof systems using lysimeters. They found that the observed runoff reduction ranged between 2% and 100% for the total runoff depth and between 17%-100% when the peak runoff rate was considered with higher reductions in deeper substrates or lower soil moisture content. Additionally, they found that the correlation to the SCS-CN model was generally high and varied from 88 to 95.5, with the lowest CN value of 0 for the vegetated system with a deeper substrate depth.
- Bliss et al. (2009) monitored a green roof and a conventional roof in Pittsburgh, PA, to evaluate stormwater runoff mitigation. Results from real-storm event monitoring showed the green roof reduced runoff volume to 70% and peak flow rates from 5% to 70% lower when compared to the conventional roof.
- Fassman-Beck et al. (2016) evaluated curve numbers and runoff coefficients for extensive living roofs using paired rainfall–runoff data for up to 21 living roofs with varying configurations and in different climates. Using a subset of the data, they found that meaningful runoff was not generated for many small storm events. They suggested a step function when evaluating with the CN method, where (1) runoff volume = 0 for design rainfall events up to 0.8-1.2 inches (20-30 mm), and (2) runoff volume with CN = 84 for larger rainfall events. They also found Cv increases with rainfall depth and can be reasonably evaluated using an empirical equation [a*exp(b/P)] with regression coefficients (a, b) based on climate zone.
- Mentens et al. (2006) investigated rainfall-runoff relationships for annual and seasonal time scales by analyzing 628 data records of different types of roofs (intensive green roofs, extensive green roofs, gravel-covered roofs, and non-greened roofs) from other publications to derive empirical models for assessing runoff using annual runoff regression equations. They found that the depth of the substrate layer strongly determines annual rainfall-runoff relationships and retention on green roofs is influenced seasonally (lower in winter than in the summer). Additionally, their review (summarized in Table 2 of the article shows a summary of data records substrate layer depth vs. runoff characteristics for the different roof types) estimated annual rainfall-retention capability from 75% for intensive green roofs (median substrate depth of 150 mm) to 45% for extensive green roofs (median substrate depth of 100 mm) compared to 25% for gravel roofs and 15% for non-green roofs, and that key factors influencing the magnitude of the retention depend on the structure of the green roof (layers and depths), climatic conditions, and the amount of precipitation.
- Maryland Department of the Environment published guidance to support stormwater design of green roofs in March 2018 following revisions to the Maryland Stormwater Management (SWM) regulations. MDE considers green roofs to be alternative surface types that are used to mitigate impervious cover, more closely mimic hydrology, and contribute to meeting environmental site design requirements in the region. They provide a summary of two effective curve number (CN) tables used in their region – effective CN by roof thickness (in) and effective CN by retention (in), of which, the latter is being newly recommended for ESD.
- Roehr and Kong (2013) investigated how unique climatic conditions affect runoff reduction functions and compared performance from three unique geographic locations (Vancouver, BC; Kelowna, BC, and Shanghai, P.R. China) using three methods – SCS Curve Number, crop coefficient method, and the Hargreaves-Samani method – to calculate annual water gains and losses during an average precipitation year as well as a soil water balance model to investigate irrigation requirements for different planting types. Their analysis showed typical green roofs could reduce annual rooftop runoff by 29% in Vancouver, 55% in Shanghai, and 100% in Kelowna, and further

highlighted the importance of factors that soil properties, soil depth, and plant selection have on green roofs and irrigation requirements.

- Guo et al. (2014) developed and applied analytical equations to evaluate long-term average runoff reduction rates and irrigation requirements for extensive and intensive green roofs with and without storage layers through probabilistic models. The detailed analytical model approach and application of continuous runoff simulations showed that the performance of green roofs may vary widely with different hydrologic designs under arid and humid climate conditions.
- Liu et al. (2020) assessed four test plots of green roofs to evaluate runoff retention of extensive green roofs using runoff coefficients and curve numbers with respect to substrate moisture. The analysis compared vegetated roofs and bare roofs with wet and dry substrates. Results found average runoff retention for vegetated roofs to be 35%-48% for dry substrate and 15-30% for wet substrate, with bare roof retention of 65% for dry substrate and 35% for wet substrate. The mean runoff coefficients of dry and wet vegetated roofs were 0.58 and 0.75, respectively. For vegetated green roofs, average CN values ranged from 93 to 97 and 96 to 98 for dry and wet substrates, respectively, with the bare green roof average CN of 93 for dry and 97 for wet substrates.
- Lee et al. (2015) evaluated the quantity and quality of 4 types of pilot facilities (acryl, concrete, and 2 green roof models in Seoul, Korea. Based on 7 rainfall events in 2011 to evaluate effects of reducing runoff using a rainfall simulator, they found extensive green roof systems achieved between 14%-61% reduction in runoff for the total rainfall (43%-61% for 200-mm soil depth; 14%-34% for 150-mm soil depth). Additionally, they found through a correlation analysis that delayed occurrence time and antecedent dry days had a significant relationship with improving water retention capacity and that high rainfall intensity had a negative effect on delayed occurrence time in the green roof system.
- Baryla et al. (2017) assess the retention ability of three extensive green roofs with different substrate compositions and a reference roof from June to November 2016 using an experimental setup. They found average runoff coefficients for green roof types (0.31 to 0.33) to be much lower when compared to the control roof (0.70 to 0.95) and that during high rainfall, the differences between the green roofs and reference roofs were less noticeable. The literature review as part of the experimental study discusses how green roofs can reduce runoff by 60% to 100%, depending on the type of green roof system used, and results from the experiment confirmed that green roofs may have a significant effect on retention and elongation of the drainage waves in urbanized areas.
- Gregoire et al. (2011) evaluate runoff quantity and quality from an extensive green roof paired with a control roof in Connecticut. They found the green roof retained 51% of precipitation during the study period with area extrapolation. Additionally, they found during their review of additional studies (Figure 1; n=13) an average precipitation retention of 56% with a minimum of 35% and a maximum of 70%. Related to design parameters, they also found significant relationships in a handful of studies between precipitation – discharge = watershed evapotranspiration and % retention based on an R-squared value of 0.88.
- Shafique et al. (2016) performed a field study to evaluate runoff quantity from both a blue roof and a green, blue roof in Seoul, Korea, along with a control roof. Their study investigated two actual storm events and showed outflow reduction from the blue roof of 0.45 L/s compared to the common roof of 1.55 L/s (intensity of 90 mm/hr). When comparing the green blue roof to the control roof, they found a reduction in outflow (0.1 L/s to 0.3 L/s) during a storm with a maximum intensity of 60 mm/hr. Although there were only two records from this study, they suggest results of

their runoff monitoring that the green, blue roof is capable of handling long-duration rain events and can delay stormwater runoff compared to the blue roof.

- Shafique and Luo (2019) performed a comparison study in 2019 to evaluate green roofs, blue roofs, and green blue roofs. They discuss in their analysis retention from 10-60% and 30-68% for green roofs and blue green roofs; however, they do not provide values for blue roofs. Instead, they elaborate on the fact that blue roofs are effective in small rain events for a shorter time period and only provide temporary storage to retain runoff for a longer time duration.

Based on the above review, a proposed value of 95% is recommended for blue roofs. This value, the same value recommended for conventional roofs, was selected for blue roofs because they are typically designed to provide capture of small storm events (i.e., water quality events); however, they only temporarily store and slowly release runoff. Once that volume is occupied, runoff occurs freely. Additionally, there is limited research on the runoff coefficients for just blue roof systems as most literature focuses on either a combination of blue-green roofs or discussed limitations with reducing runoff volume and focus on peak flow reduction through slow release of stormwater.

Based on the above literature review, proposed values for green roofs of 65% and 50% are recommended for extensive and intensive green roof systems, respectively. Green roof systems have varying ranges for runoff coefficients and runoff reduction capabilities that are often dependent on green roof design factors such as substrate depth and substrate types, along with other climatic conditions such as storm characteristics and geographic location. Depending on the green roof system, the designer may want to consider discussing or adjusting imperviousness values per manufacturer recommendations or performing additional research specific to the green roof system.

<u>Permeable Pavement Systems</u>

Permeable pavement systems, including pervious concrete, permeable asphalt, porous gravel pavement (PGP), reinforced grass pavement (RGP), and porous interlocking concrete pavement (PICP), are designed to allow water to infiltrate into the subsurface and reduce surface runoff during storm events. There are many types of permeable pavement systems; however, this memorandum will group these into two categories: PICP and CGP/PGP/RGP. Other pavement types, such as permeable asphalt, are currently excluded from the USDCM.

Key findings suggest that the runoff coefficients of permeable pavement systems vary depending on factors such as pavement material, design characteristics, site conditions, and maintenance practices. Permeable pavement systems have lower runoff coefficients compared to conventional impervious surfaces and demonstrate potential to reduce stormwater runoff volumes and peak flows. However, factors such as surface clogging, compaction, and sediment accumulation can reduce infiltration rates and increase runoff coefficients over time further highlighting the importance for regular, effective maintenance practices to maintain the hydraulic properties.

In comparison with surfaces listed in WWE's memorandum, permeable pavement systems are best aligned with gravel areas. Recommended values discussed in WWE's memorandum (2023) are subdivided by different applications and use cases, which resulted in recommended values of 40% (no traffic areas – pedestrian use), 60% (low traffic areas – maintenance paths and substations), and 80% (high traffic areas – roadways and parking). These values, in combination with a review of the literature, will be used to recommend percent imperviousness for the different permeable pavement systems.

The Interlocking Concrete Pavement Institute (ICPI) provides extensive research on different types of permeable pavement systems. ICPI's "PICP for Design Professionals Fact Sheet" (2008) suggests the NRCS Curve Number (CN) and Rational Method runoff coefficients (C values) depend on the soil infiltration rate, base storage, and design storm, and present CN values of 45-80 and C values of 0.00-0.30 for PICP compared to CN values of 95-98 and C values of 0.90-0.95 for impervious asphalt and concrete pavement. The fact sheet highlights research related to volume reduction that demonstrated PICP can reduce runoff as much as 100% from a 3-inch rainfall event with a sandy soil and minimum 12-in thick open-graded aggregate base. Additionally, PICP can reduce annual outflows between 30% and 80%, and well-maintained PICP can reduce flow rates by 70% to 90% with up to 100% for many storms depending on regional variations in annual storm events and PICP base storage capabilities as well as delay and reduce peak flow by as much as 89%.

Additional findings from the literature review are summarized below:

- Marchioni and Becciu (2015) performed a detailed review of available literature and summarized experimental results for assessing the role of permeable pavement in urban drainage based on full-scale tests related to runoff volume reduction and quality improvement. The paper summarizes in multiple tables runoff coefficients from different references. Runoff coefficients for grid and PICP systems ranged from 0.00 to 0.45 (see Table 2). They also investigate research on design life and maintenance and found one study that concluded after 20 years, a permeable pavement could lose 80% of its initial infiltration rate.
- Selbig et al. (2019) evaluated the stormwater quantity and quality of three lined permeable pavement systems – PICP, PC, and PA – over a 22-month period in Madison, WI. A total of 95 measured runoff events were captured; however, limited runoff data related to runoff coefficients was incorporated into the paper as it focused more on quality and clogging potential over a period. More importantly, the literature review of other studies in this paper highlighted key elements of different types of systems and the design components of those systems, specifically lined and unlined systems. The authors highlight one phenomenon that was supported by several studies related to runoff reduction for full infiltration systems. They state: "Field tests on the performance of this scenario have shown dramatic reductions in pollutant concentration and load because much of the water filtering through the permeable pavement exfiltrates into underlying soils thereby producing zero effluent for most runoff events (Brattebo and Booth, 2003; Bean et al., 2007; Roseen et al., 2012; Drake et al., 2014a; Braswell et al., 2018; Shafique et al., 2018). While this scenario would result in a 100 percent removal efficiency, it does not properly assess the pollutant removal capabilities of the permeable pavement and underlying aggregate subbase." This is an important statement when evaluating the runoff reduction capability of lined and unlined systems with respect to both stormwater quantity and quality.
- Alyaseri and Zhou (2016) evaluated pre-construction and post-construction runoff reduction of three types of permeable pavement systems installed in three alleys with underlying clayey soils in St. Louis, MO. Results showed runoff reduction percentages of 36%, 13%, and 46% from the permeable concrete, permeable asphalt, and permeable pavers, respectively.
- Shafique et al. (2018) evaluated retrofitted permeable pavement in a highly developed area of Seoul, Korea. Field observations and data were collected and reported for a PICP system to evaluate rainfall-runoff relationships, including rainfall intensity with respect to runoff volume reduction performance and peak flow. Based on their work, overall runoff reduction performance from PICP

was around 30%-65% across all storm events and showed 100% volume reduction with rainfall intensity of 40 mm/hr and 30-50% reduction with rainfall intensity of 120 mm/hr. The study also found a significant reduction in peak flows in an urban area (average of 10-25%). The hydrologic performance of the PICP system is suggested to be influenced by the underlying soils.

- Alam et al. (2019) studied hydrologic performance of three types of permeable pavement systems – Porous Concrete Pavement, PICP, and Interlocking Block Pavement with Gravel (IBPC) – in semi-arid south Texas and compared results to adjacent traditional pavements at different regional parking lots. Results suggested average runoff reduction compared to traditional pavement of 87-98% (PCP), 46-88% (IBPG), and 80-96% (PICP). Additionally, there are several important studies referenced in this paper related runoff reduction and peak flow reduction for the most commonly used types of permeable pavement – PC, PA, PICP, CGP, and PRGP. One study found no runoff from PC surface for rainfall events from 30 mm (Wilmington, NC), while other studies found PCP and PICP can reduce peak flow by 60-74% and 77-89%, respectively.
- Støvring et al. (2018) evaluated lined permeable pavement systems through a field monitoring study using four types of permeable pavement products and three subbase aggregates (six combinations in total). They found total volume reduction with an impermeable liner ranged from 3 to 37 percent based on a 12-month monitoring period and discussed the influence of both surface and subsurface properties with respect to hydraulic properties of the different permeable pavement systems.

Based on this information, proposed values of 45% and 55% are recommended for the design of PICP and grid systems, respectively. The key factors in maintaining runoff coefficients are directly related to effective maintenance practices and how the system receives runoff. These values also consider the design life as infiltration rates will start high and will decline over time.

<u>Extended Detention Basins (EDBs)</u>

EDBs are intended to be dry stormwater facilities used to collect, store, and slowly release runoff during storm events. EDBs generally have structural elements that increase imperviousness and receive sediment collected from stormwater runoff over time. The Runoff chapter of the USDCM (2024) recommends using a value of 20% for managed turfs and disturbed soils. However, to account for the influence of accumulated sediments within an EDB over time and account for other structural elements such as trickle channels, maintenance paths, forebays, and outlet structures (all of which are hardened surfaces), a proposed value of 25% is recommended for EDBs.

<u>Receiving Pervious Areas (RPAs)</u>

RPAs (including grass buffers and grass swales) promote onsite infiltration and support runoff reduction by disconnecting impervious surfaces. To align with recommended imperviousness values by surface types for managed lawns and turfs (disturbed soils), a value of 20% is recommended for these areas.

<u>Bioretention & Sand Filters</u>

Bioretention and sand filters are infiltration and filtration systems. These systems are designed with high infiltration rates compared to grass and gravel areas. Considering the hydraulic properties of soil media, which are predominantly sandier soils (HSG A soils) and based on field observations at research sites, water can effectively infiltrate into the subsurface during storm events. The bioretention media used in the Denver metropolitan region is based on a sandy soil mix that supports vegetation and promotes infiltration. The root structure of the vegetation facilitates increased infiltration rates into the media and helps maintain infiltration over time. Due to the sand content of these systems, they provide more significant runoff volume reduction than other pervious surfaces. Research by Battiata et al. (2010), which was used to support future USDCM Runoff chapter updates related to imperviousness values by surface type and also used in different criteria manuals in the United States, such as the Minnesota Stormwater Manual, provides volumetric runoff coefficients by land use (forest cover, disturbed soils, and impervious cover) and soil groups (A,B,C,D). Volumetric runoff coefficients for disturbed soils vary by soil type (A=0.15, B=0.20, C=0.22, and D=0.25). Corresponding to HSG A soils in these accepted values and considering additional benefits due to the nature, hydraulic properties, and application of bioretention systems and sand filters as discussed above, a proposed value of 10% is recommended for these SCMs.

Conclusions

Based on our review of multiple types of literature sources, academic research, criteria from across the nation, and field observations on MHFD monitoring sites, percent imperviousness values for SCMs can vary based on several factors including geographic location, design storm characteristics, and stormwater control measure characteristics. For consistency in the Denver metropolitan region, MHFD represents adopting a regional value. Table 1 presents the recommended imperviousness values for different SCMs.

Recommendations for Percent Imperviousness of Stormwater Control Measures

Type of Stormwater Control Measure	Percent Imperviousness (%)
Retention Ponds & Constructed Wetland Ponds	100
Rooftop Systems - Blue Roofs	95
Rooftop Systems - Green Roofs - extensive	65
Rooftop Systems - Green Roofs - intensive	50
Permeable Pavement - CGP/PGP/RGP	55
Permeable Pavement - PICP	45
Extended Detention Basin	25
Receiving Pervious Areas (Grass Buffers & Grass Swales)	20
Bioretention & Sand Filters	10

Regarding how these numbers are applied, it is important to note that the values presented in Table 1 are percent imperviousness values for stormwater control measures; they are not runoff coefficients. Refer to the USDCM for more information about the difference between percent imperviousness and runoff coefficients and their use cases in different hydrologic design methods, such as CUHP and the Rational Method.

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