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RESEARCH ARTICLE

Dynamic design of green stormwater infrastructure

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HIGHLIGHTS

- Research shows GSI Practices outperform static volume crediting.
- Recommend including exfiltration and evapotranspiration for dynamic design.
- Expand design to include climate, in situ soil and vegetation to take advantage of GSI Properties.

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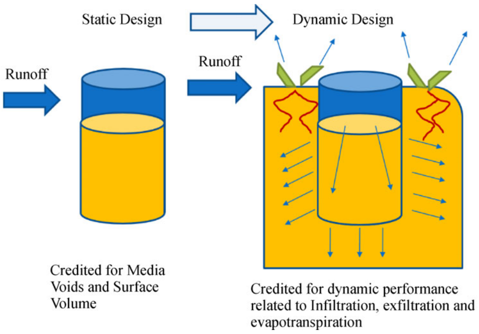
GRAPHIC ABSTRACT



ABSTRACT

This paper compares ongoing research results on hydrologic performance to common design and crediting criteria, and recommends a change in direction from a static to a dynamic perspective to fully credit the performance of green infrastructure. Examples used in this article are primarily stormwater control measures built for research on the campus of Villanova University [1,2]. Evidence is presented demonstrating that the common practice of crediting water volume based on soil and surface storage underestimates the performance potential, and suggests that the profession move to a more dynamic approach that incorporates exfiltration and evapotranspiration. The framework for a dynamic approach is discussed, with a view to broaden our design focus by including climate, configuration and the soil surroundings. The substance of this work was presented as a keynote speech at the 2016 international Low Impact Development Conference in Beijing China [3].

1 Introduction

Design and crediting of stormwater management practices to mitigate the deleterious urbanization runoff effects has dramatically changed from a narrow flood control peak flow focus toward a broader sustainable approach focused on the components of the hydrologic cycle to include water quality. The movement from traditional stormwater practices such as detention basins, to Low Impact Development (LID) now incorporates green infrastructure techniques to include stormwater wetlands, pervious pavements, green roofs and bioretention cells, etc. Green stormwater infrastructure (GSI) in urbanized areas includes soil-water-plant systems that utilize the components of the hydrologic cycle to mitigate urbanization impacts by reducing and treating stormwater runoff at its source while delivering environmental, ecological, social, and economic benefits. As our experience with these systems grows, it is becoming clear that to maximize performance and minimize costs we need to consider all components of the physical processes and tools to include landplaning.

The use of green roofs, rain gardens and pervious pavements was accelerated in the United States when a stormwater rule was announced [4] addressing for the first time on a regulatory basis the need to permit non-point

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sources of pollution. While all areas have differing climates and water challenges, it was quickly realized that to properly understand and mitigate the impacts of urbanization, runoff volumes needed to be included. Pennsylvania published their Comprehensive Stormwater Policy including volume as a mitigation requirement in 2001. This was followed by a National Research Council Report in 2009 [5] that firmly addressed the need to address the hydrologic changes in volume, and the Federal Energy Act [6] required federal projects to remove smaller volumes from surface flows to achieve "preconstruction hydrology."

2 Current situation: static design

Early design requirements were conservative, in part due to the lack of research available. Using bioretention or rain garden as an example, early adopters first credited the surface storage (bowl volume), though most have moved to crediting the available soil storage as well. This approach is considered as static in nature and does not include the benefit of exfiltration from the media into the in situ soil during the storm event, and does not incorporate evapotranspiration (ET) into the design process. Also, the static approach does not take into account the effects of regional climate on the performance of stormwater control measures (SCMs). A design concern regarding the regional climate has been the variability of infiltration rates with temperature (i.e., seasonal change) and the effect of back to back storms on reducing performance of SCMs [7]. As an example, current design and permitting procedures for rain gardens in Pennsylvania are based on a static approach, meaning that they only account for static stormwater runoff volume storage by surface storage and fill media void space during a rain event [8, 9]. Philadelphia Stormwater Management Guidance Manual [10] states that the planting soil texture in rain gardens should conform to sandy loam or loamy sand in USDA triangle classification system. Philadelphia Water Department uses a static porosity-based approach for calculating the bioretention soil volume credit based on 20% void space [11].

3 Better-than-expected performance

Looking at the performance monitoring results of several SCMs at Villanova University indicates that in most cases the SCMs have exceeded the static design expectations. A study by Lord (2013) of the hydrologic performance of an undrained bioinfiltration SCM (i.e., rain garden with no underdrain and lining) demonstrated the performance of this SCM based on a static design (Table 1). This SCM was designed to remove runoff from 2.5 cm rainfall events over the contributing impervious area. Half of this volume would be captured in surface storage, and half in the soil void space. Exfiltration during the storm event was not considered in the design [8,9,13]. Lord's study reviewed 364 storms and found an overall volume reduction of 82%. What is more impressive is that the site met the design intent removing 100% by volume of rainfall events of the size approximating surface capture, and 97% of storms that exceeded the surface capture but were less than the combined capacity of the surface and soil void space. For rainfall events less than the design volume there was no apparent adverse impact on the expected performance from back to back rainfall events. This is supported by a more recent study by Wadzuk et al. who found that the risk of reduced performance due to a previous event is relatively rare for regions with similar climates [14]. Lord (2013) also noted that for events larger than the static design, the

Table 1 Villanova bioinfiltration SCM performance [12]

storm size (cm)	sample size	average volume reduction
small (< 1.27)	115	100%
medium (1.27–2.54)	127	97%
large (> 2.54)	122	50%

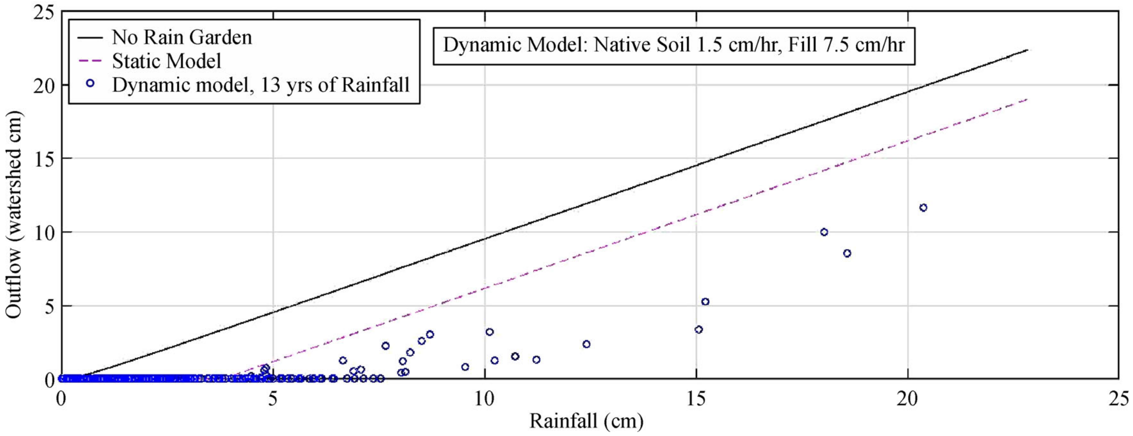

Fig. 1 Bioinfiltration dynamic performance [21]

SCM removed 50% storm volume. Other studies by the first author with collaborators found similar results [7,14–16].

4 Dynamic design

These results have shifted our focus toward examining the importance of exfiltration during storm events as well as the role of ET in drying the soil and the recovery of infiltration capacity. Lewellyn et al. found that routinely vegetated infiltration systems greatly exceeded design expectations during extreme events, and Lee et al. related the soil media properties to that of the underlying in situ soil infiltration capacity [17,18]. It is clear from these and previous works that exfiltration during storm events is important. For areas where substantial back-to-back storms are rare, not only does a portion of the stormwater runoff retained go to infiltration and ET immediately after a rainfall event, but also during dry time ET is further reducing the amount of moisture within the soil and thereby restoring the capacity of the system to store stormwater for the next rainfall event. This is a key point that has been neglected in continuous models of stormwater control measures [19]. Although ET is generally greater after a rain event than during dry periods, ET continues during relatively dry periods as long as water is available that is presently not credited when SCMs are evaluated and permitted [20]. Accounting for ET in the design of bioretention SCMs has its own challenges as well. ET is a continuous and variable process and does not easily fit into the existing static design approach for bioretention sizing. In reality, the recovery mechanism of soil infiltration capacity in rain gardens depends on ET as well as exfiltration from the soil media to the underneath and surrounding native (in situ) soil. Static design does not include the benefits of exfiltration during the storm event and ET in the recovery of infiltration capacity. A continuous simulation dynamic model is needed for the design of rain gardens and other GSI practices to take full advantage of what they offer. The dynamic design approach needs to consider the hydrologic and soil properties during and between storm events.

5 Dynamic design example

As an attempt to perform the dynamic design approach, a conceptual model was developed for a bioinfiltration SCM with a 10:1 impervious to SCM footprint and 3.8 cm (1.5 in) static capture (i.e., soil void space and surface storage) [21]. Infiltration from surface to the fill media and exfiltration from fill media to the underneath native soil was considered in the model. To reduce the complexity of the model, no ET or side exfiltration to the surrounding native soil was considered, and the site was expected to recover completely between storms. The fill media and native soil were assumed to contain hydrologic soil groups A and C, with a saturated hydraulic conductivity of 7.5 and 1.5 cm/h, respectively. Figure 1 shows the results of this dynamic model using the rainfall record of the Villanova site. As the solid line shows, the runoff volume in the case of no rain garden (i.e., 100% impervious drainage area) is almost the same as rainfall volume. The slight difference between rainfall and runoff volume in this case is attributed to the initial abstraction of rainfall. The dashed line in Figure 1 corresponds to the static design model of rain garden, when no exfiltration to the native soil is considered. The circles, which correspond to different storm events in the dynamic design model, clearly show the improved performance of the rain garden against a wide range of rainfall depths in the dynamic approach. The added performance should be credited for this design. As mentioned before, this dynamic model does not include ET and side exfiltration to the surrounding native soil. Adding those two components to the model should further improve the results.

6 Major research questions

Moving toward dynamic design causes a number of questions that need to be addressed. The most important research questions regarding the dynamic design approach can be summarized as follows.

1. What would a framework for dynamic design look like?
   a. What SCM design parameters would be added or affected?
   b. What processes are required to be modeled?
2. How would a dynamic design performance be evaluated?
3. Is there a difference in risk for dynamic versus static design?
4. What would be the implications of dynamic design in climate change and resilient infrastructure?
5. What modeling/design tools are needed to implement dynamic design?

The answers to many of these questions are currently being explored. For example, it is clear that infiltration, evapotranspiration, rainfall patterns and multiyear climate processes need to be included in the answer to Question 1. What is less clear is the interplay of plants, winter seasons, inspection and maintenance practices, and sediment loading. Research on these topics is emerging. The evaluation (Question 2) and risk projection (Question 3) are intertwined, and are projected to be performance based, but policy research is needed in conjunction with regulatory authorities. Question 4 clearly builds upon our understanding of climate and risk, but also depends upon understanding of the expected changes of weather and its effect on vegetated systems and rainfall patterns. Question

5 then relates back to question one, but contains elements of all four questions that precede it.

7 Next generation design of GSI

An essential need as expressed in question 2 is to develop performance assessment criteria for dynamic design. For example as stated earlier, common standards are tied either to a rainfall volume, or to an extreme storm event. To meet a dynamic volume standard, a continuous simulation over a set period of years could be used to demonstrate that no event (or a minimal percentage) exceeded this volume over that time period. Similar approaches could be developed for pollutant based design, integrating water quality and water quantity approaches. The design storm approach would need a longer term simulation, and would need to be based upon risk. All of these approaches need to start with continuous simulation, and have the advantage that changing patterns can be introduced into the simulation.

In addition to exfiltration that is a main component for a dynamic design, seasonal changes of infiltration rates and effect of back to back storms on reducing performance of SCMs are design considerations. Looking at the general framework for dynamic design of a SCM such as rain garden indicates that many climatic, environmental, soil, water, plant, site, and human factors can affect the overall performance of the SCM. In contrast to the static design approach that considers a rain garden as a simple practice with two components of bowl and void space, a rain garden is a complex system of components and processes related to climate, environment, soil, water, plant, site conditions, drainage area, and human factors in which, components have several connections and interrelationships. Malfunctioning or property change of each component can affect the overall performance or longevity of the system. In addition to the use of dynamic design approach, next generation design of GSI systems should look at the different components of each GSI system and consider them in the design process to maximize performance. As a general example, the most important components/processes of a rain garden as a widely-used GSI system in urban areas, are identified and categorized as follows.

1. Climate/season: Rainfall pattern: Antecedent moisture: Change in soil hydraulic conductivity: Water availability for plants and ET
2. Inflow/runoff: Loading ratio: Land cover/land use: Effective impervious area: TSS/particle size distribution: Pretreatment/trash collection systems: Inlet capture efficiency
3. Overflow: Destination: Conveyance method
4. Outflow (underdrain): Need: Restricted vs unrestricted
5. Plants: Type: Root structure/depth: Physiology: Morphology: Ecology: Aesthetic
6. Maintenance activities: Inflow sediments and debris: Plant health: Compaction
7. Surface storage: Volume: Geometry
8. Fill media: Organic Layer: Soil type / characteristics: Balance between engineered and in situ (native) soils: Soil layers: Geometry- Depth vs. width: Infiltration-ET balance: Long-term infiltration rate: Recovery mechanism of infiltration capacity
9. Rock bed storage: Need: Configuration: Protection
10. Evapotranspiration (ET)
11. Infiltration: Model: From surface to the soil: Between soil layers: Soil water characteristics: During/between events
12. Exfiltration: Model: From fill media to the surrounding/underneath soil

Figure 2 depicts different components of a typical rain garden system. It should be noted that the above-mentioned factors have been presented mostly based on a “runoff volume reduction” point of view. Considering the “water quality” aspects of a rain garden would result in a more complex system with more components and processes. In an ideal case, next generation design of GSI systems would consider all of the above mentioned components and integrate them into the design process. From a dynamic design point of view, incorporation of regional climate, ET, and exfiltration in the recovery mechanism of soil media during and between events are the most important issues that need further research.

8 Discussion: advantages and disadvantages of static and dynamic approaches

Both the Static and Dynamic Approaches have advantages and disadvantages. What is an advantage for one is usually a disadvantage of the other. For example, the static approach is simpler. Estimating the surface and soil storage is simpler than a continuous simulation of the soil vadose zone and plant evapotranspiration. This is of tremendous value to many uses, for community and smaller projects, and areas that are not space constrained. A dynamic approach would tailor the SCM to the site surroundings, and would configure the SCM to maximize the infiltration and evapotranspiration processes. This would require more effort in design, and field testing of soil exfiltration rates. The simpler approach would be expected to produce larger designs, and may require additional components such as underdrains or rock beds due to uncertainty. The dynamic approach would more rigorously evaluate the need for these added components, and would be expected to generate smaller SCMs, increasing the possible locations within the restrictive urban environment. A dynamic approach could also be tailored to promote ET, in areas where infiltration is not desirable, or to address varied pollutant loadings. Oversizing of static design can be considered as a safety factor, usually more addressed

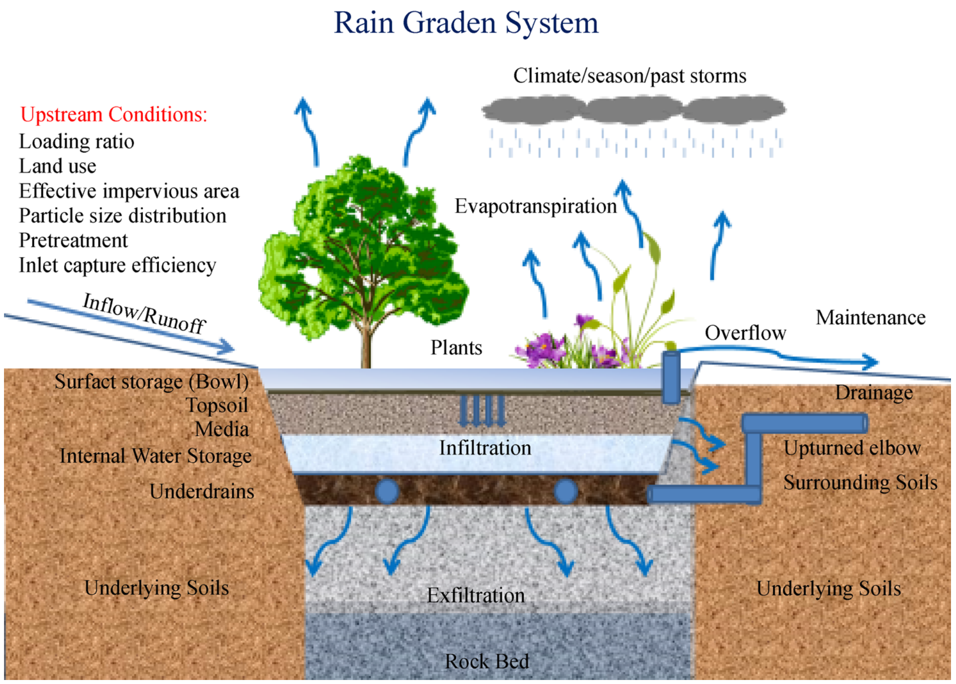

Fig. 2 Rain garden system (Drawing: Carla Windt)

toward flooding resilience. The question is how effective is this additional capacity, as the SCM design is not evaluated to maximize potential exfiltration performance, and the "extra" capacity is not designed to a standard. When designing for flooding resilience, a systems approach looking at the performance with regards to the overall infrastructure should be considered superior. In many cases, the advantages of static versus dynamic design may rest upon the site environment and climate, and design objective.

9 Summary

In summary, research has shown that the static approach routinely underestimates the performance of volume reduction green stormwater infrastructure practices. Consideration of regional climate, exfiltration during storm events, and evapotranspiration is needed to both fully credit GSI systems, and to maximize performance in the design. We are terming this approach as the dynamic approach to stormwater design. Moving toward dynamic design will increase the SCM performance in larger storm events and reduce the SCM size and cost, making it possible to build more facilities within the same budget. In addition, next generation design of GSI systems would consider all of the climatic, environmental, soil, water, plant, site, drainage area, and human components of the GSI system and integrate them into the design process. From a dynamic design point of view, incorporation of regional climate, ET, and exfiltration in the recovery mechanism of soil media during and between events are the most important issues that need further research. Current focus is on developing design tools to predict the performance of GSI systems, and on setting criteria for assessment. Examples from current research on green infrastructure sites at Villanova University and in the Philadelphia region will be used as a basis for this work. Further information on these research sites is available at www.villanova.edu\VUSP.

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References

1. Villanova Urban Stormwater Partnership. VUSP ~ PaDEP – Best Management Practice National Monitoring Site- Year 12, 2015
2. Villanova University Villanova Urban Stormwater Partnership. Villanova Urban Stormwater Partnership – Research. Villanova University 2016, Available online at http://www.villanova.edu/villanova/engineering/research/centers/vcase/vusp1/research (accessed Dec. 30, 2016)
3. Traver R. Stormwater Green Infrastructure, where have we been and

how far can we go? Keynote Presentation, Beijing: 2016 International Low Impact Development Conference, 2016

4. USEPA.Stormwater Phase II Final Rule – Fact Sheet, USEPA Office of Water, Washington, DC, 2000
5. National Research Council.Urban Stormwater Management in the United States. Washington, DC: National Academies Press, 2009
6. USEPA.Technical Guidance on Implementing the Stormwater Runoff Requirements for Federal Projects under Section 438 of the Energy Independence and Security Act, USEPA Office of Water, Washington, DC, 2009
7. Emerson C, Traver R. Multiyear and seasonal variation of infiltration from stormwater best management practices. ASCE Journal of Irrigation and Drainage Engineering, 2008, 134(5): 598–605(2008)134:5(598)
8. Pennsylvania Department of Environmental Protection.Pennsylvania Stormwater Best Management Practices Manual. PaDEP, Harrisburg, PA, 2006
9. Zukowski Z. Evaluating rain gardens of different configurations and infiltration testing methods to determine rain garden design and site investigation recommendations. Master Thesis, Villanova: Villanova University, 2016
10. Philadelphia Water Department.Stormwater Management Guidance Manual, Version 3.0. PWD 2015
11. Philadelphia Water Department.Stormwater Regulation Updates, July 2015, Available online at http://www.phillywatersheds.org/StormwaterRegulations (accessed Dec. 30, 2016)
12. Lord L. Evaluation of Nitrogen Removal and Fate within A Bioinfiltration Stormwater Control Measure. Master Thesis, Villanova: Villanova University, 2013
13. Heasom W, Traver R G, Welker A. Hydrologic modeling of a bioinfiltration best management practice. Journal of the American Water Resources Association, 2006, 42(5): 1329–1347
14. Wadzuk B, Lewellyn C, Lee R, Traver R. Green Infrastructure Recovery: analysis of the influence of back-to-back rainfall events. ASCE Journal of Sustainable Water in the Built Environment, 2017, 3(1):04017001
15. Davis A P, Traver R G, Hunt W F, Lee , R, Brown R A, Olszewski J M. Hydrologic performance of bioretention stormwater control measures. ASCE Journal of Hydrologic Engineering, 2012, 17(5): 604–614
16. Lee R, Traver R, Welker A. Continuous modeling of bioinfiltration stormwater control measures using Green and Ampt. Journal of Irrigation and Drainage Engineering, 2013, 139(12):1004–1010
17. Lewellyn C, Lyons C, Traver R, Wadzuk B. Evaluation of seasonal and large storm runoff volume capture of an infiltration green infrastructure system. ASCE Journal of Hydrologic Engineering, 2015, 21(1):04015047
18. Lee R, Traver R, Welker A. Evaluation of soil class proxies for hydrologic performance of in situ bioinfiltration systems. ASCE Journal of Sustainable Water in the Built Environment, 2016, 2 (4):04016003
19. Wadzuk B M, Traver R G. Soil moisture balance in bioretention systems. Proceedings of the Water Environment Federation, 2012 (5), 231–240
20. Wadzuk B, Schneider D, Feller M, Traver R. Evapotranspiration from a green-roof storm-water control measure. ASCE Journal of Irrigation and Drainage Engineering, 2013, 139(12): 995–1003
21. Lee R. A look at the hydrologic design of rain gardens. Unpublished Philadelphia Water Department Presentation, 2016