Dynamic processes in urban green infrastructure systems

Approches dynamiques pour les infrastructures vertes urbaines

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RÉSUMÉ

Les infrastructures vertes urbaines (IVU), en tant que solutions de gestion durable des eaux pluviales, sont dynamiques et variables en raison des processus hydrologiques dominants -infiltration et evapotranspiration (ET). Les approches de conception traditionnelles, basées sur le volume, ne tiennent pas compte de ces processus, ce qui entraîne des projets surdimensionnés ou des systèmes inefficaces. Nous examinerons quatre études de terrain portant sur différents types de IVU, bassins versants, et différentes périodes. Tous les sites démontrent que les systèmes IVU bien entretenus peuvent capter plus d’eaux pluviales que prévu lors de la conception. Adopter une approche de conception dynamique permettrait d’harmoniser la conception et la performance observée, menant à des conceptions qui peuvent respecter les réglementations de manière efficace et économique.

ABSTRACT

Urban green infrastructure (GI), a sustainable stormwater management solution, is dynamic and variable due to the primary hydrologic processes - infiltration and evapotranspiration (ET). Traditional, volume-based design approaches do not incorporate these processes, resulting in overdesign that minimizes accepted crediting for the systems or inefficient systems. Four field studies are examined representing a range of GI types, watersheds, and time. All sites reliably demonstrate that well-maintained GI systems regularly can capture more rainfall than their design capture. Moving to a dynamic design approach will more closely align the design and observed performance, which will result in designs that can efficiently and economically meet regulatory requirements.

KEYWORDS

Dynamic design, hydrology, green infrastructure, stormwater, urban systems

1 INTRODUCTION

Urban green infrastructure (GI), such as bio-infiltration basins and infiltration tree trenches, use components of the hydrologic cycle to manage stormwater runoff and mitigate the effect of urbanization. These GI systems are soil-water-plant systems that are dynamic and variable. The hydrologic processes, primarily infiltration and evapotranspiration (ET), vary over time (i.e., by season and annually) and space (i.e., within a GI system and regionally). However, we have traditionally designed GI with a volume-based approach without incorporating the true dynamic hydrological nature of these systems. The typical goal of infiltrating GI design is to capture runoff, infiltrate it into the subsurface, and restore the infiltration capacity before the next storm event. The volume-based GI design considers available subsurface void space, surface ponded area, and a set time duration for drawdown, but ignores the active, dynamic nature of water flow through the system.

Extensive GI monitoring in Philadelphia and Villanova, PA indicates the importance of dynamic interevent exfiltration and ET in recovering infiltration capacity and the temporal and spatial variability of system performance (Emerson and Traver, 2008; Hess et al., 2017). High hydrologic performance of GI systems has been observed by others around the world, which is attributed to heterogeneities in infiltration rates and ET (e.g., Davis et al., 2009; Lucke and Nichols, 2015; Jiang et al, 2017). The dynamic nature is exemplified by a series of small, frequent rainfall events may diminish the soil infiltration capacity for the next event or variable ponding time that may be different throughout the year is response to the same size event. As experience and knowledge of GI systems grow, to maximize performance and minimize cost, next-generation designs need to incorporate these processes and interrelationships in a GI system. Dynamic design of GI requires continuous simulation and includes exfiltration during storm events, ET, and surface and subsurface storage. Regional climate (e.g., seasonal variability of infiltration rates and storm event characteristics) is also considered in the dynamic approach. Benefits of moving to dynamic design are to promote more efficient and economical GI in the restrictive urban environment and properly account for GI performance under a range of storm sizes (Traver and Ebrahimian, 2017). Field monitoring results are compared between a volume-based design versus a dynamic design, and to demonstrate how the volume-based design may underestimate urban GI performance. Further, a framework for dynamic design is presented.

2 SITES

2.1 Bio-infiltration basins

Bio-infiltration basins are the most recommended GI in urban environments as runoff enters from the roadway/adjacent surface and infiltrates in to the native soil directly. These GI systems typically require minimal infrastructure relative to other GI. One bio-infiltration basin used is a retrofit of an existing traffic island at Villanova University in Villanova, PA (Figure 1). The basin watershed is 5261 m^2 and is 44% impervious with a 10:1 loading ratio (directly connected impervious area to GI treatment area). Water level in the system has been monitored since 2003. The second bio-infiltration basin studied is in Philadelphia and has a 1161 m^2 drainage area with a 11:1 loading ratio. It has been studied since 2016.

Figure 1. Bio-infiltration basins (left) Villanova and (right) Philadelphia.

2.2 Tree trenches

A stormwater tree trench, a common GI in Philadelphia, PA, is a system of tree pits that are connected by an underground continuous stone trench. Runoff enters the system through an inlet and is distributed into the tree trench through a perforated pipe. Runoff is designed to be stored in the stone trench, water the trees, and exfiltrate into the surrounding soil. One tree trench located in Philadelphia, PA, has a 100% impervious 1743 m^2 drainage area (Figure 2) that has a 20:1 loading ratio (“Hartranft”). Water level in the system has been monitored since December 2012. A second tree trench, also located in Philadelphia, has a 2650 m^2 drainage area and has been monitored since 2015. Overflow volume was not measured at these sites and therefore only number of overflow events is reported.

Figure 2. Tree trenches in Philadelphia (left) Hartranft and (right) Morris Leeds.

3 PRELIMINARY RESULTS

Monitoring results show that these four different systems, designed differently and at different times, all “over-performed”, meaning that they were all able to capture more than what they were designed to capture using a volume-based approach (Table 1). The historical design capture depth in this area is 25 mm, which is about 50% of the annual rainfall events.

Table 1. Capture Performance of GI

Site	Volume-based design capture depth (mm)	# observed overflows (# total events)	Rainfall depth causing observed overflow* (mm)
Villanova bio-infiltration	25	26 (1023)	25
Philadelphia bio-infiltration	42	5 (48)	51
Hartranft tree trench	23	12 (399)	37
Morris Leeds tree trench	48	0 (62)	---

*There were events larger than this depth that did not cause overflow; dependent on antecedent dry time and time of year.

Each GI system has fewer overflow events observed than designed for with the volume-based approach. For example, in the Villanova bio-infiltration basin, in 2013 there were four observed overflow events, five overflow events when simulated considering dynamic processes, and 12 overflow events when simulated using the volume-based approach. Similar trends were seen in other years and at other sites. Further, the rainfall depth that causes an overflow is typically substantially greater than then design. In the Villanova bio-infiltration basin, the 25 mm event that had overflow had a very short antecedent dry time. Using a continuous simulation that can capture the dynamic hydrologic processes more closely mimics observations.

4 DISCUSSION

A framework is being developed to incorporate dynamic processes in to the traditional volume-based design approach. Regulations have not yet met up with the science and a continuous simulation to demonstrate design performance is not a widespread requirement. Thus, to take advantage of the dynamic processes within the existing regulatory standards and to more properly size and credit GI to make these systems more economical, a framework is suggested. The Villanova bio-infiltration and Hartranft tree trench were analysed under continuous simulation over several years and for individual storm events, typical of the volume-based design approach. Peak matching in terms of depth and duration, as well as the recession rate, were used to compare the continuous simulation with the individual event performance. The individual event, volume-based models tended to overpredict overflow duration that was observed at each site and predicted by the continuous simulation. Based on findings from calibrating the continuous simulation model to the observed data, the infiltration rate was used to calibrate the individual event, volume-based model to develop a model that more closely replicated observed performance. This procedure led to a framework that a designer could use to use the traditional volume-based approach to better incorporate the dynamic processes with a GI system. The basic process entails 1) choosing a representative, local rainfall distribution; 2) choosing a representative infiltration rate (via saturated hydraulic conductivity values) for a site and allow it to vary over the year; 3) applying the volume-based design approach and iterating the design capture volume until the system overflows to a) resize the system to meet the capture requirement or b) credit for a larger than required capture volume. Choosing an infiltration rate involves uncertainty. It is suggested to move to using simplified field tests, such as the Modified Phillip-Dunne, which is quicker and easier than the standard double-ring infiltrometer and enables multiple tests performed in a day to capture site heterogeneity (Ahmed et al., 2014). Based on observed infiltration data, seasonal multipliers are applied to the volume-based approach to quantify the range of expected performance over the year. The first two steps are critical because they match up local rainfall patterns with the temperature varying infiltration process. For example, in the Philadelphia, PA area, most rainfall falls during the summer when temperatures are higher and infiltration rates are elevated. Dynamic design can take advantage of this relationship to not unduly use an overconservative design method.

5 FUTURE WORK

The proposed methodology that incorporates the key aspects of dynamic design (i.e., exfiltration to the surrounding soil, seasonally variable infiltration rates, and realistic rainfall distributions) into an event- (volume-) based simulation model must be further calibrated and verified. Considering this approach will enable not only the design to more towards a more dynamic and realistic method, but it can also start to inform the dynamic operation and maintenance of the GI systems. Maintenance is a key element in ensuring that a GI system lasts through its design life, however, it is also a large cost burden. Using a dynamic approach to consider seasonal effects to guide maintenance scheduling and tasks can streamline widespread municipal maintenance plans and minimize costs.

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