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Urban stormwater characterization, control, and treatment

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Abstract

This review summarizes over 250 studies published in 2018 related to the characterization, control, and management of urban stormwater runoff. The review covers three broad themes: (a) quantity and quality characterization of stormwater, (b) control and treatment of stormwater runoff, and (c) implementation and assessment of watershed-scale green stormwater infrastructure (GSI). Each section provides an overview of the 2018 literature, common themes, and future work. Several themes emerged from the 2018 literature including exploration of contaminants of emerging concern within stormwater systems, characterization and incorporation of vegetation-driven dynamics in stormwater control measures, and the need for interdisciplinary perspectives on the implementation and assessment of GSI. © 2019 Water Environment Federation

Practitioner points

- Over 250 studies were published in 2018 related to the characterization, control, and treatment of stormwater.
- Studies cover general stormwater characteristics, control and treatment systems, and watershed-scale assessments.
- Trends in 2018 include treatment trains, vegetation dynamics, and interdisciplinary perspectives.

Key words

hydrology; low impact development; runoff; stormwater control measures; water quality

Introduction

With increasing urbanization and the future impacts of climate change, the effective control and management of stormwater runoff is a challenge of significant importance around the globe. The solutions to these issues are complex and require a holistic view of water quantity and quality concerns. This includes both location-specific stormwater control measures (SCMs), such as stormwater ponds and wetlands, and watershed-scale stormwater control and management utilizing sustainable green stormwater infrastructure (GSI) and low impact development (LID).

The objective of this review was to provide an overview of the most impactful literature on stormwater control and management published in 2018. In an effort to allow direct comparisons with previous years, this review follows the structure of Moore, Rodak, Ahmed, and Vogel (2018). The review begins with a discussion of new literature as it pertains to stormwater quality and quantity, providing the background needed to discuss stormwater control and management. Following this are seven sections focused on SCMs including erosion and sediment control, constructed stormwater ponds, constructed stormwater wetlands, bioretention, permeable pavement, green roofs, and rainwater harvesting. Following individual SCMs, the review transitions to watershed-scale LID assessments which focus on the combined impacts of GSI. Lastly, a number of innovative research papers are highlighted relevant to the topic of stormwater but falling outside the sections defined above, and the review concludes with general observations on trending topics from the 2018 literature.

General Stormwater

Stormwater understanding is essential to inform efforts to control and manage stormwater and its impacts on aquatic ecosystems. Over 25 papers were published in 2018 regarding the physical, chemical, and biological characteristics of stormwater and how these characteristics are influenced by land use and other environmental factors. The following sections provide an overview of literature published in the topical areas of stormwater quantity and quality.

Quantity

The implementation of green infrastructure continues to grow in towns and cities across the globe. Research published in 2018 examined infiltrated stormwater and its impacts on groundwater systems. Researchers aimed to quantify the connection between infiltration-based stormwater management approaches to groundwater recharge. One geographic area selected for study is in Maryland, USA, and is composed of bioretention facilities and recharge chambers. By monitoring several wells in the area and conducting water table fluctuation analysis, researchers determined that well proximity to nearby streams and storm properties impacted episodic recharge to precipitation ratios (Bhaskar, Hogan, Nimmo, & Perkins, 2018). Other researchers evaluated an 1,800-m^2 infiltration basin via a network of piezometers over a three-year period. They found that in the warmer months, much of the infiltrated stormwater evapotranspired, while some infiltrated stormwater did reach downslope streams in the cooler months (Bonneau et al., 2018).

Quantification of an area's overall drainage basin, location of sinks, contributing watershed, and accumulated downstream flow were the results of research where a terrain model was processed using ArcGIS (raster, vector, and geometric network processing). The researchers were able to highlight the power of using terrain data (Balstrøm & Crawford, 2018). A different study focused on a stormwater pipe network in an urban setting to determine the performance of looped systems and branched systems. Data from five different catchments and over 400 historic rainfall events were used with the EPA-Stormwater Management Model (SWMM), and simple linear regression was employed to determine relationships between the variables. A looped system was found to be able to more quickly drain a catchment area but is comparatively denser with more pipe installations per unit area, which would in turn increase the operation and maintenance efforts (Lee, Chung, Chung, Park, & Park, 2018).

Research sought to evaluate modeling uncertainty due to rainfall, model parameters, and routing methods. InfoWorks Integrated Catchment Modeling rainfall–runoff model was used, and the uncertainty from model parameters including rainfall was analyzed. The results noted that systematic errors had more influence on peak flow and runoff volume compared with random errors (Gong, Li, et al., 2018). Researchers also sought out to understand the uncertainty in runoff estimation within the U.S. Environmental Protection Agency's National Stormwater Calculator. Case studies of 12 urban areas in the United States were analyzed. One of the goals of this calculator is to determine rainfall–runoff relationships. The researchers noted that the calculator generally underestimated hydraulic conductivity for the 12 cities of the study. It was also determined that if LID occurred on high permeability soil, nearly all of the pre-LID runoff was treated (Schifman, Tryby, Berner, & Shuster, 2018).

The beneficial use of stormwater remains an important topic of research in 2018. The use of dry wells was investigated with the HYDRUS software package for numerical modeling and with falling head and infiltration experiments. The modeling results and experiments showed the ability to characterize hydraulic properties in the soil using the experiments and model methodology and thus would assist in improving the design of dry wells for aquifer recharge (Sasidharan, Bradford, Šimůnek, DeJong, & Kraemer, 2018). Researchers in South Africa used isotopic tracing of the Liesbeek River to determine the origin of wet weather flows in the area. Researchers analyzed isotopic compositions of water samples via wavelength-scanned cavity ring-down spectroscopy with results, indicating that a large proportion (>90%) of streamflow during a wet weather event is due to rain events. The researchers point out that stormwater harvesting would be beneficial to capture and appropriately make use of this water supply (van Mazijk, Smyth, Weideman, & West, 2018). Another study analyzed four optimization algorithms to identify an appropriate strategy to rehabilitate the drainage system in eastern Tehran, Iran. The researchers applied relief tunnels and storage units within the urban area and evaluated multiple algorithms (NSGA-II; NSHS; NSDE; and AMALGAM) finding the AMALGAM model resulted in better convergence and diversity (Yazdi, Mohammadiun, Sadiq, Neyshabouri, & Gharahbagh, 2018).

Quality

Researchers examined ongoing land use and land cover modifications occurring in a development in South Korea. Stormwater samples were collected and analyzed, ArcGIS was used for catchment delineation, statistical analyses were performed to determine relationships between the variables, and SWMM was employed to determine the impacts of land use on stormwater quality. The results showed that many of the pollutants had higher concentrations during early land development activities, but anthropogenic pollutants were observed at higher concentrations in later stage land development (Paule-Mercado et al., 2018). Other researchers looked toward life cycle assessment (LCA) tools and whether they appropriately considered urban stormwater impacts. The researchers compiled the various pollutants, precipitation data, and impacts and determined how these environmental impacts can be placed in the LCA model. The researchers concluded that materials of construction and other related parameters can significantly impact LCA results (Phillips, Jeswani, Azapagic, & Apul, 2018).

A driver for research this past year, and previous years, was finding a marker to track fecal pollution. Research performed in Australia designed crAssphage qPCR assays to detect wastewater pollution. The two marker genes, CPQ_056 and CPQ_064, provide sufficient specificity due to their high concentrations and low variability. In a study of a lake in Australia, researchers found that greater amounts of the markers were found during wet weather events which may indicate wastewater pollution and urban stormwater runoff are being transported to the lake from overflow points (Ahmed, Payyappat, Cassidy, Besley, & Power, 2018).

A stormwater research target in 2018 was improving the value of modeling activities. Researchers used the Urban Runoff Branching Structure (URBS) model and incorporated methodology to include the temporal and spatial variability of the buildup and wash-off processes. Researchers defined wash-off parameters at the beginning of wet weather events for various land use types and noted that fluctuations and trends in the total suspended solid (TSS) values were accurately simulated (Al Ali, Rodriguez, Bonhomme, & Chebbo, 2018). Modeling of the buildup of benzene series compound on roadways was studied, motivated by human health risks tied to benzene, toluene, ethylbenzene, and xylene (BTEX). Dry and wet vacuuming methods were used to gather samples and tested in the laboratory using gas chromatography–mass spectrometry, along with other analytical tests. BTEX buildup was then modeled using an artificial neural network approach and regression modeling approaches (i.e., multiple linear and multiple nonlinear). The artificial neural network approach performed the best and was able to denote pollutant locations and related health risk maps (Hong et al., 2018). Researchers studied ways to improve calibration of stormwater quality models and found that TSS event load distribution may be used especially when data limitations exist. Results of the study that looked at flat roof and parking lot experimental sites found that the models were able to be calibrated using the Kolmogorov–Smirnov distance measure (Leutnant, Muschalla, & Uhl, 2018).

Contaminants of emerging concern in urban runoff and stormwater was a focus of some researchers in 2018. An inventory of stormwater-based contaminants of emerging concern from stormwater samples in Minneapolis-St. Paul, Minnesota, USA, found 123 detected compounds that showed seasonal and site-specific traits. The researchers identified profiles of each, such as warm weather scenarios where the main contaminants of emerging concern are herbicides. The use of iron-enhanced sand filters reduced many hydrophobic and polar-hydrophilic compounds (Fairbairn et al., 2018). Researchers in Germany focused their research on biocides (e.g., diuron, terbutry, and octylisothiazolinone) and related products that have origin uses as facade preservatives. Grab samples were collected from swales following wet weather events as well as groundwater wells. Results showed that facility facades are biocide sources throughout their life and can contaminate groundwater systems (Hensen et al., 2018).

The use of electrochemical oxidation for pretreated stormwater disinfection was evaluated for efficacy. The experimental setup included a dimensionally stable anode using iridium and ruthenium oxides–titanium oxides. Synthetic stormwater and real stormwater from a stormwater biofilter were used to evaluate and validate disinfection performance. The results appear promising with low energy consumption (e.g., 0.018 kWh per ton of stormwater treatment), but deterioration of the anode occurred quickly likely because of the low salinity levels and it was determined that chlorination was the key disinfection mechanism (Feng, McCarthy, Wang, Zhang, & Deletic, 2018). Further research on the use of electrochemical oxidation evaluated how stormwater chemistry was impacted by the use of this disinfection process. Results on stormwater samples pre- and post-electrochemical oxidation showed disinfection byproducts below Australia's Drinking Water Guidelines and that performance was positively correlated to initial pH value (Feng, McCarthy, Henry, et al., 2018). A separate study conducted in Australia examined stormwater runoff from urban areas focusing on the nitrogen composition. Twelve field monitoring stations with autosamplers were deployed with analyses of nitrite, nitrate, total Kjeldahl nitrogen (TKN), and other compounds performed after sample collection. The results showed that TSS, total nitrogen (TN), and total phosphorus (TP) in runoff from residential and commercial areas appeared to be significantly lower than current stormwater management policy in Australia. Additionally, the researchers found that organic nitrogen was the largest percentage of the TN metric. The results may point to evaluating current treatment measures and approaches such that designers can optimize sizing (Lucke, Drapper, & Hornbuckle, 2018).

The quality of stormwater runoff from a road versus a pavement was evaluated using various laboratory meters to measure pH, turbidity, color, conductivity, nitrate, and total solids. The first flush samples were tested and compared to the runoff metric of rainwater. The samples from the pavement showed high nitrate and turbidity values while road surfaces had a higher electrical conductivity (Fernando & Rathnayake, 2018). Research conducted in Beijing, China, gathered samples at various locations at sites including city roads, gas stations, and residential areas, and then analyzed the samples using various analytical methods, including gas chromatography–mass spectrometry. Researchers found that the concentration of volatile organic compounds (VOCs) decreased from highway junction, to city road, to gas station, to park, to campus, and to residential area. Statistical analyses indicated that land-use type and precipitation time intervals may significantly impact VOC concentrations (Li, Wang, et al., 2018). In 2018, researchers also studied particle size distribution of road-deposited sediments as the distribution may impact a selected treatment solution. Road-deposited sediments and stormwater samples were captured, and laboratory experiments and statistical tests were conducted. The researchers identified the quotient of turbidity/TSS as a surrogate for particle size distribution (Wang, Zhang, Dzakpasu, et al., 2018).

A study conducted in Poland aimed to determine the impact of stormwater runoff on macroinvertebrates. Several analytical methods were performed to capture a range of metrics from dissolved oxygen (DO) to TP. Macroinvertebrates were sampled at the five stations and identified according to the Water Framework Directive. The results showed that *Ephemeroptera*, *Trichoptera*, and *Mollusca* were sensitive to stormwater runoff contaminants such as heavy metals and organic matter and stormwater-related impacts were greatest in shallow reservoirs as opposed to rivers (Gołdyn et al., 2018). Researchers in Sydney examined the biodiversity of the Sydney Harbour estuary and the impacts of stormwater on these communities. The phytoplankton community was studied using nucleic acid extraction and bioinformatics analyses. The researchers found that a greater diversity of phototrophs was identified during wet weather events noting that such events may encourage biodiversity (Varkey et al., 2018). Another research group studied the impact of iron-enhanced sand filters on mitigating stormwater toxicity using two model organisms (*Daphnia magna* and *Pimephales promelas*). The researchers found that seasonality played a role in performance with concentration of metals and nutrients lower in the late summer and with the sites that used iron-enhanced sand filters (Westerhoff et al., 2018).

Stormwater researchers in 2018 explored the evaluation and identification of unique sources of stormwater pollutants. A study conducted in Sweden aimed to evaluate stormwater runoff from an airport. Given the amount of fluids used in aircraft deicing/anti-icing during the winter, the study sought to determine how an infiltration pond performed and how sampling could be conducted under these conditions. Using an autosampler, several parameters were measured such as TN, TP, cations, perfluorinated chemicals, jet fuel components, and pesticides. The results showed that fluctuations in flow associated with cold climates make stormwater discharge sampling challenging. The winter season results showed that a large portion of nitrogen was stored in snow which would then release during snowmelt and heavy rains. This would then be followed by minor emissions in the drier months (Jia, Ehlert, Wahlskog, Lundberg, & Maurice, 2018). Another study looked at stormwater pollution originating from atmospheric phase heavy metals that contribute to stormwater pollution via the pathways of atmospheric buildup, atmospheric dry deposition, atmospheric wet deposition, and road surface buildup and wash-off. The results showed that if atmospheric phase heavy metal concentrations are not included in pollutant loading estimations, the values may be underestimating the true loadings in particular for zinc which had the highest load in all four of the transport pathways (Liu et al., 2018). Researchers examined development in Charlotte, North Carolina, USA, to determine sediment denitrification in streams in an effort to quantify how stormwater control measures are impacting these conditions. Samples were taken from locations upstream and downstream of the receiving streams with sediment analyses, stream water analyses, and denitrification assays conducted. The results indicated that stormwater control measures play a valuable role as a transitional point from impervious urban areas to a stream network by providing in-stream nutrient processing (Rivers, McMillan, Bell, & Clinton, 2018). Researchers also identified stormwater contamination associated with the secondary disinfectant, monochloramine. Following sampling and analysis activities, the researchers studied the monochloramine loss mechanisms and found that stormwater dissolved organic matter from various locations had similar compositions and that humic material was the dominant source (Zhang, Davies, Bolton, & Liu, 2018).

Common themes and future work

Research published on general stormwater topics in 2018 examined both quantity and quality themes. The beneficial use of stormwater remains an important resource, and many researchers examined locations around the globe to study what options may be available for more effective uses of captured stormwater. Researchers continued to investigate various stormwater-related models to ascertain whether they are accurately representing parameters, exploring whether non-traditional stormwater models would benefit from including a layer of stormwater impacts, and evaluating the amount of uncertainty in the models. Contaminants of emerging concern and the exploration of under-researched pollutant sources was another common theme this year as researchers examined overall stormwater quality. Future research will likely be driven by work to refine models, quantify or reduce uncertainty, and explore pollutants of emerging concern in stormwater to determine their health implications and concentrations.

Erosion and Sediment Control

In 2018, there were at least 12 published studies related to erosion and sediment control. Heavy precipitation and increasing urbanization can result in increasing erosion and sediment transport. Erosion control is defined as practices which prevent the formation and propagation of erosion over varying landscapes while sediment control focuses on practices which contain sediment and protect sensitive aquatic ecosystems.

Erosion control

Prevention of erosion is the best control method whenever possible. On sloped terrain, vegetation can have a significant impact on the occurrence of erosion and sediment release. Over the course of 15 years, simple grass strips were found to be a cost-effective solution to reducing erosion in a citrus orchard in China when compared to clean tillage, intercropping, and level terracing (Tu, Xie, Yu, Li, & Nie, 2018). The greatest reduction in sediment load was seen in the first 4 years. Chen et al. (2018) also looked at the role of vegetation in erosion control. After studying nine plots of different vegetation on the Loess Plateau in China, it was determined that grassland provided the best erosion protection, demonstrating a 92% reduction in soil loss over 43 events in 9 years. Reduction in soil loss was found to correlate with ground cover; therefore, shrubs also provided good erosion protection compared to forested area with minimal ground cover. Li and Pan (2018) explored the role of grass species even further comparing three species of grass in 5m x 2m plots on a 25-degree slope. Compared to bare soil, the grasses reduced sediment loss by 67.1%. It is estimated that 84% of this reduction is contributed by the root biomass after comparing various grass conditions of fully intact, stem and roots, and roots only.

Erosion control is also necessary in areas prone to gullying such as agricultural land (Frankl, Prêtre, Nyssen, & Salvador, 2018). A study of the implementation of boundary vegetation in northern France found that while the introduction of boundary vegetation demonstrated a 31%–85% reduction in gully length, this finding was not statistically significant due to widespread heterogeneity. In addition, if boundary vegetation was poorly maintained, gullies may simply bypass the vegetation, continuing the erosion. A review of soil and water conservation practices in Ethiopia found that unless gully formation is directly addressed and halted, erosion control is unlikely to be successful (Ayele et al., 2018).

Predicting the occurrence of erosion can also be beneficial. Tao, Wang, and Lin (2018) developed a model to predict overland flow and soil erosion which utilized the kinematic wave model. Compared to other models, the sediment dynamics only require a runoff erosion calibration constant and a slash erosion calibration constant. The model showed good accuracy when predicting runoff, but showed decreased accuracy when predicting sediment dynamics. This is likely due to the complexity of predicting and modeling sediment transport.

In areas with rapid growth, erosion can occur quickly. Asiedu (2018) assessed the threat of erosion using the RUSLE model in Accra, Ghana. This process required the production of several maps related to rainfall–runoff erosivity, soil erodibility, slope length and steepness, vegetation, and conservation practices. The region was found to have a soil loss classification considered "high." However, this high soil loss classification was clustered in approximately 10% of the study area providing critical spots where erosion control should be implemented. Justin, Bergen, Emmanuel, and Roderick (2018) utilized GIS, field investigations, resident questionnaires, and interviews with officials to assess the effectiveness of the stormwater infrastructure in Dar es Salaam in Tanzania, a region which had recently undergone rapid growth. It was determined that despite significant presence of erosion gullies, erosion control was not seen as a priority in the region.

Sediment control

There are several methods to trap and contain sediment prior to transport to aquatic systems. Some methods utilize natural products, and as such, it is important to confirm that these approaches do not release more harmful compounds into the environment. Egbujuo, Fullen, Guerra, and Opara (2018) explored the geochemical characteristic of biogeotextiles used for sediment collection and erosion control. Because biogeotextiles are left in the environment, it is important to consider their potential to release compounds to the environment as they degrade. Using X-ray diffraction and X-ray fluorescence, it was determined that biogeotextiles contained macronutrients which could be released to the environment such as Mg, K, P, Ca, and S and none of the products tested contained trace metals.

Sometimes, the optimal sediment control method is not clear due to the role of soil type, slope, rainfall, and material composition. Lee, McLaughlin, McLaughlin, Whitely, and Brown (2018) investigated the differences between straw, hydromulch, and polyacrylamide (PAM) application on erosion control and grass growth. After collecting information on runoff volume, turbidity, eroded sediment, nutrient concentration, and grass establishment, no statistically significant conclusion could be found. Although no impact was seen from the use of PAM in the previous study, Kang, Vetter, and McLaughlin (2018) found the introduction of cationic and nonionic PAM into construction site runoff reduced effluent turbidity in a sedimentation basin by 98% and 90%, respectively. Where applicable, nonionic PAM is recommended as cationic PAM may pose an aquatic threat. It was shown that basic jar tests can provide guidance on the efficiency of different PAM compounds as well as the appropriate dose for a sedimentation basin. Al-Ani (2018) created a decision support system to design dry and wet sediment basins for Malaysian construction sites. The tool determines whether a dry or wet basin is needed depending on soil type and then sizes the basin, emergency spillway, sediment trapping efficiency, and maintenance frequency. The design results were validated against those provided by experts and were found to be in good agreement.

Common themes and future work

In 2018, a wide range of work related to erosion and sediment control occurred. Prediction and prevention are the ideal solutions for rapidly urbanizing areas and more work is anticipated, particularly toward the development of erosion mapping. There is an opportunity for incorporating the performance of sediment control devices into other related water quality metrics.

Constructed Stormwater Ponds

Constructed stormwater ponds (CSPs) are a stormwater management technique employed to reduce peak stormwater flows, usually prompted by new urbanization, with a focus on stormwater retention and detention. These ponds also have water quality and ecological benefits which have become a source of interest. In 2018, there were at least 17 publications focused on the function and potential benefits of CSPs.

Water quality

Constructed stormwater ponds have a clear impact on stormwater retention and detention, but their role in water quality treatment and the resulting impact on downstream watercourses are less clear. For example, imperviousness is an important factor when determining water quantity needs. In Krakow, Poland, a CSP was monitored for a wide range of nutrients, trace metals, and micropollutants (Wałęga & Wachulec, 2018). Chemical oxygen demand (COD), suspended solids (SS), and chlorides were found to be crucial water quality parameters for stormwater runoff from roads. Although trace metals were also analyzed and are commonly associated with roadway runoff, they were dropped from the analysis due to insufficient data quantity. In a study of water quality of 19 CSPs, Brink and Kamish (2018) found that percent imperviousness had no correlation to metal (Cd, Cu, Pb, and Zn) and TSS removal efficiencies. The study did determine the efficiency of removal was impacted by the magnitude of the influent mass loads and that the volume of the permanent pool, and the ability to settle and avoid resuspension, was an important factor in removal efficiency. Significant removal rates of 35%, 63%, and 84% for Zn, Cu, and Pb, respectively, were also demonstrated in a single pond study in Northern France (Ivanovsky et al., 2018). Metal influent concentrations were extremely low, supporting the observation of good removal rates with low influent loads, but the influent demonstrated significant variability. Additional parameters were also measured during the study including polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyl (PCBs), caffeine, carbamazepine, nutrients, and pathogens. Despite high concentrations in the sediment of heavy PAHs, PCBs, and metals at the entrance to the pond, monitoring of the downstream watercourse demonstrated a negligible impact.

Nutrients are also a significant area of interest when looking at the water quality impact of CSPs and are often impacted by processes occurring with the sediment. In a laboratory study, two cores from CSPs with different management protocols and organic matter content were studied to determine the role of bioturbating invertebrates on nutrient cycling (Kuntz & Tyler, 2018). In all of the columns, reactive inorganic nitrogen was released into the water column. This process was more pronounced during the colonization phase, suggesting this may be more significant during the initial construction of a CSP or following dredging of an aged pond. Schroer, Benitez-Nelson, Smith, and Ziolkowski (2018) quantified carbon, nitrogen, and phosphorus sources and sinks in 14 residential CSPs of varying age in South Carolina. Terrestrial biomass was found to drive the sediment source type, even in CSPs with significant algal productivity, and the sediment accumulation was found to correlate with the percent imperviousness of the basin. Regionally, these ponds were estimated to sequester carbon, nitrogen, and phosphorus in the sediments at rates similar to lakes: 2.0×10^9 g C/year, 9.5×10^7 g N/year, and 3.7×10^7 g P/year.

Sediments also contain trace metals and micropollutants and can therefore act as a toxin for aquatic life. Wiest et al. (2018) investigated the presence of 44 substances in sediment from a detention basin in an industrial area in France. Overall, two pesticides (chlorpyrifos and diuron) and four polybrominated diphenyl ethers were detected in quantifiable amounts but only infrequently. More common was the presence of alkylphenols and bisphenol A (BPA) occurring in every sample between concentrations of 6 ng/g and 3,400 ng/g. The alkylphenols correlated with anaerobic conditions and BPA with increased total organic carbon and fine sediment. Interestingly, no increase (accumulation) in the contaminants was seen.

The *Heterocypris incongruens* bioassay for ecotoxicity estimation was implemented in an industrial CSP near Lyon, France (Becouze-Lareure et al., 2018). The CSP was sampled at five locations multiple times over 5 years. Although there was minimal temporal and spatial variation, the sampling location at the sediment chamber at the pond demonstrated significantly greater ecotoxicity, suggesting the fresh sediment holds a greater risk to the aquatic community.

Biotoxins can also be generated within the pond by bacterial activity within the sediment. Strickman and Mitchell (2018) studied the seasonal, spatial, and intra-pond variability of methylmercury (MeHg) in CSPs of varying age. Methylmercury is a bioaccumulative neurotoxin and was found in greater concentrations in a 15-year-old pond when compared with a 6-month-old pond and a 15-year-old pond which had recently been dredged. Concentrations of MeHg were found to positively correlate with sulfate and negatively correlate with nitrates, suggesting production from sulfate-reducing bacteria which had time to colonize and thrive in the older CSPs.

Given the role of sedimentation and nutrient dynamics within CSPs modeling, these processes are also a focus within the literature. A 2D hydrodynamic full shallow water model coupled with advection–diffusion for fine suspended sediment load calculations was proposed and validated with three laboratory-scale experiments (Guan, Ahilan, Yu, Peng, & Wright, 2018). The model was then used to predict sediment behavior in a CSP in Newcastle, UK, under 5-year, 30-year, and 100-year scenarios. Although additional work is needed to capture complex sediment behavior in the system, the model is a step toward understanding sediment dynamics in CSPs.

Some of the complexity in sediment behavior may come from vegetation within the CSP. Sonnenwald, Guymer, and Stovin (2018) used a moment sink approach coupled with experimental data of dispersion around vegetation and the computational fluid dynamics model Fluent to explore residence times for various pond configurations. The study found that the CSPs behaved more like plug flow reactors and that plant location was a more important parameter than precise characterization of the plant itself. Araújo and Lima Neto (2018) also identified behavior more similar to plug flow conditions when analyzing BOD and COD concentrations in a CSP in Brazil. The studied CSP had high BOD and COD concentrations indicative of wastewater inputs. The removal efficiency of the CSP could be described by the Reynolds number, and when a modified removal efficiency based on Reynolds number was incorporated, the BOD could be modeled as a plug flow reactor with first-order decay.

Design and management for optimization

Modeling the performance of CSPs is not just associated with treatment capabilities. Many researchers have started to look at “Smart stormwater systems” and the role of active control of CSP outlets to reduce peak flows. Bilodeau, Pelletier, and Duchesne (2018) studied the hypothetical addition of a CSP upstream of a newly urbanized area in Granby, Quebec, Canada. The addition of a smart stormwater system was shown to reduce peak flows by 46%, detain water on average 36hrs longer compared with passive conditions, and use up to 22% less of the downstream collector at the newly urbanized area. Parolari, Pelrine, and Bartlett (2018) focused in on the CSP itself, developing a model for both passive and active control using a stochastic water balance model to determine probability density functions of water level and valve closing times for active systems. Although a step toward modeling smart stormwater systems, some model limitations identified including simplifications of basin geometry, assumptions of Poisson arrival processes which may or may not be valid depending on location, and limited data to calibrate parameters.

In Ann Arbor MI, USA, Mullapudi, Bartos, Wong, and Kerkez (2018) looked to create and characterize a low-cost open-source smart stormwater system using two controlled CSPs to mitigate peak flows downstream of the ponds (open-storm.org). The outlets of both CSPs were first modified for control ($3,500/outlet) and then the resulting pulse from a release of stormwater from each CSP was characterized. Inspired by pulse-width modulation used in electrical systems, the outlets were then controlled in an effort to create a flat hydrograph by staggering releases and evening out peak flows in the downstream watercourse.

Constructed stormwater ponds also support ecological functions, the extent of which are determined by a number of morphological, biotic, and abiotic factors as discussed in the review by Clevenot, Carré, and Pech (2018). Due to the complexity and interaction of the factors, it can be difficult to predict whether a CSP will provide a positive or negative impact on various ecological functions. Holtmann, Juchem, Brüggeshemke, Möhlmeyer, and Fartmann (2018) found that CSPs had a positive impact on the richness and density of dragonflies in North Rhine-Westphalia, Germany. When compared to control ponds, CSPs were larger, warmer, and had lower phosphate concentrations which had positive impacts on the species richness. This was attributed to less woodland cover due to regular maintenance around the ponds, resulting in greater sunlight on shallower average depths. Miro, Hall, Rae, and O'Brien (2018) found that stormwater features with long durations of wetness, such as CSPs, had greater ecological quality as measured by amphibian, macrophyte, and macroinvertebrate richness. The occurrence of CSPs and greater ecological richness also correlated with socioeconomic indicators associated with affluent neighborhoods.

Common themes and future work

In 2017, there was a noticeable lack of metal removal studies, but in 2018 several water quality studies looked at a wide range of pollutants including trace metals. Unique to this year was a significant focus on sediment quality and modeling. These year studies sought to document the ecological impacts of CSPs, an area with mixed conclusions in the past years and therefore remain an important topic of study. Noticeably absent from the literature this year were studies focused on retrofits of existing CSPs; based on literature in 2018, it is predicted that studies focused on Smart stormwater systems via active outlet control and studies of ecological function of CSPs will increase in future years.

Constructed Stormwater Wetlands

In 2018, 23 publications focused on constructed stormwater wetlands (CSWs). Constructed stormwater wetlands utilize a combination of shallow surface flow and densely populated regions of plants to reduce stormwater volumes along with pollutant concentrations. The CSW publications cover a wide range of topics from short- and long-term performance, hybrid constructions, model development and testing, and optimization of floating CSWs.

Field, laboratory, and modeling performance studies

Contaminant fate in CSWs was the focus of two studies. The sorption of heavy metals to sand substrates in CSWs was investigated through a laboratory and field-based study (Walaszek, Bois, Laurent, Lenormand, & Wanko, 2018a, 2018). The work showed that sand had a higher affinity and greater removal of Pb and Cu compared with Zn. Pb and Cu removal was affected through the formation of hydroxyl groups of iron oxides complexes on the sand surface. Zn was shown to desorb easily after initial adsorption to sand. The fate of phosphate through a 0.3 ha CSW showed a gradual reduction in median concentrations from inlet (0.066 mg/L) to outlet (0.022 mg/L) during baseflow, and no decreases during storm events (Komlos, Vacca, & Wadzuk, 2018). Additionally, there was a poor correlation between sediments and phosphate, hypothesized to be linked to the low sediment inputs to the CSW (Vincent, Shang, Zhang, Chazarenc, & Brisson, 2018). Phosphate accumulation in the soils of the CSW was correlated with soil organic content, and not the primary path of phosphate transport in the CSW.

The removal of pathogenic bacteria from stormwater routed through CSWs suggested that the co-removal of pathogenic and fecal indicator bacteria occurred when microbial communities at the inlet were displaced by indigenous autotrophic communities at the outlet (Huang et al., 2018). Additionally, older wetlands were found to not offer as much treatment as newer systems, implying the critical need for maintenance to ensure long-term system performance. In another study to evaluate the removal of *E. coli* and reference pathogen *Campylobacter* spp. in stormwater piped to a CSW, *E. coli* was consistently removed while *Campylobacter* concentrations in the outflow were higher than in the inflows (Meng et al., 2018). This result suggests that *E. coli* was a poor indicator for reference pathogen *Campylobacter* and implies that CSW design needs to incorporate removal of both indicator and pathogenic bacteria.

The pulsing of CSW by infrequent large storm events was investigated through two studies. The first was on a 40-ha periphyton-based CSW that was subjected to several pulsed high-flow events (Zamorano, Piccone, & Chimney, 2018). Removal efficiencies of TP were not reduced during these pulsed events, there were no increases in TP export in post-pulse storm events, and therefore the overall performance of the CSW was not impacted by the high-pulse perturbations. In another study, TN and TP exports after a hurricane event yielded a 130% and 37% post-event, respectively, with measurements taken over a 6-day period (Nesbit & Mitsch, 2018). Four other smaller storm events that were measured that same water year at the same location yielded TN and TP removal, consistent with longer-term averages at the site.

Modeling of the hydraulic performance of a CSW system comprising four vertical flow beds and a free water surface system suggests that this configuration can mitigate peak flows associated with combined sewer overflow (CSO) events (Rizzo et al., 2018). Peak flow reductions were shown to range between 52.7% and 95.4%, with an 86.2% reduction associated with the 10-year flow event. A new modeling tool called Orage was developed to help optimize the dimensions of CSWs that are designed to treat CSO flows (Pálfy et al., 2018). Orage is specifically designed for vertical flow filters, simulating flow hydraulics, and removal of TSS, COD, and NH4-N with satisfactory results.

Longer-term performance

A constructed stormwater treatment wetland studied in South Florida over 12 years exhibited the formation of phosphorous-rich flocs that accumulated in depth (Zamorano, Bhomia, Chimney, & Ivanoff, 2018). The highest concentrations of these flocs, TP, and P were found at the soil surface near the inflows, while total Ca was shown to play an important role governing overall functioning of the wetland. Another study on seasonality controls on CSW performance showed that over a 3-year period, temperature, pH, DO, and redox potentials in the system were related to seasonal variability and rainfall. These conditions in turn impacted concentrations of heavy metals within the system (Walaszek, Bois, Laurent, Lenormand, & Wanko, 2018b, 2018). A long-term study expanded on an unintended consequence of CSWs, showing that CSWs constructed in ecologically sensitive areas can become traps for urban amphibians (Sievers, Parris, Swearer, & Hale, 2018). Frogs were shown to be incapable of distinguishing between CSWs and natural wetlands, thereby exposing themselves and their progeny to contaminated waters. Tadpole survival and predator olfactory cues were shown to be significantly impacted.

Design optimization and innovations

Design elements in CSW construction were highlighted in two studies published in 2018. In a study of 54 CSWs with differing topographic complexities that included islands, berms, and more traditional open and less complex flow path routing, islands clustered near the inlet had the best hydraulic performance. Also, islands occupying about 10% of the basin volume yield the maximum pollutant removal (Guzman et al., 2018). Depth, hydraulic retention time (HRT), inflow concentration, and plant species richness controlled the speciation of ionic N in CSWs (White, 2018). Design elements closely controlled redox and microbial processes in the CSW and therefore the amount of nitrogen that was in the form of NO_3–N.

Multistage treatment of stormwater by stacking specific design elements in series within a CSW was the focus of several studies. Removal efficiencies associated with a CSW fitted with a sedimentation pond followed by a vertical sand filter ranged from 50% for naphthalene to 100% for particulate Zinc (Walaszek et al., 2018). High concentrations of four heavy metals were found in the CSW during nonstorm (dry) periods, while seven heavy metals were found in the preceding sand filter during the same dry period. Heavy metal remobilization from the sand filter was found to be an issue. Including discrete elements to a CSW such as a sedimentation zone, a geochemical barrier, and a biofiltration zone improved overall removal efficiencies by 4%–10% based on two years of monitoring of a CSW in Poland. This system treated 61.4% of TSS, 37.3% of TP, 30.4% of PO_4^{3-}, 46.1% of TN, 2.8% of NH^{4+}, 44.8% of NO^{3-}, and 64.0% of Cl^- from influent stormwater (Szklarek, Wagner, Jurczak, & Zalewski, 2018). Water quality in a stormwater pond with a CSW pretreatment cell improved water quality parameters compared with a stormwater pond without pretreatment using a CSW (Natarajan, Hagare, & Maheshwari, 2018). Total solids, ammonium, and phosphate concentrations in the receiving stormwater pond improved by 50%, 62%, and 53%, respectively. A study to assess removal efficiencies associated with a multi-compartment CSW showed that removal rates were varied during and between storm events, with greatest removal during low flow events between storms. The overall removal efficiency of the study CSW was 45% for TN and 65% for TP between 2009 and 2015 (Adyel, Hipsey, & Oldham, 2018). A monitoring study that evaluated the role of a constructed pocket wetland located between a stormwater outfall and its point of entry to a receiving stream showed that the wetland was able to increase stormwater residence by 2 hr (Krompart, Cockburn, & Villard, 2018).

Several studies highlighted the importance of vegetation in CSWs. A study in Uganda showed that vegetated CSWs demonstrated the highest COD (75.9%), TN (72.8%), and TP (62.8%) removal compared with the nonvegetated control. The nonvegetated control CSW however showed the most removal of TSS (75.6%), suggesting that a nonvegetated pretreatment CSW preceding a vegetated one improves performance by limiting clogging (Kabenge, Ouma, Aboagye, & Banadda, 2018). Higher vegetation density in 19 CSWs was associated with water levels that were on average 0.35 m lower. However, water levels in the CSWs were regulated by outlet efficiency and not by inflow rates, suggesting that adjustable outlet controls driven by real-time water level sensing systems would preserve vegetation densities in the system, and improve overall performance (Robertson, Fletcher, Danger, & Szota, 2018). The relationship between nutrient removal and plant growth showed that plant growth was related to the availability of nutrients in the water for plant uptake (Vincent et al., 2018). With proximity to the CSW inlet where nutrient concentrations were highest, plant biomass was also the greatest. Plant biomass and vigor decreased with distance from inlet, suggesting nutrient depletion in the water. Overall, above ground biomass in the CSW was not a good indicator of nutrient removal rates. *Cyperus* was the plant with the most biomass and low nutrient loading conditions.

Floating treatment wetlands

A literature review of 180 studies related to floating treatment wetlands (FTW) was published by Shahid, Arslan, Ali, Siddique, and Afzal (2018) outlining the usefulness and efficacy of FTWs in treating polluted water. The synergistic roles between bacteria and plants to improve removal efficiencies were highlighted in this work. Xavier, Janzen, and Nepf (2018) conducted a numerical study to model flows around the roots of a floating vegetated raft to determine what configuration of plants on the raft achieved the best treatment. Results from this work showed that wakes generated by upstream rafts can negatively impact removal rates at downstream rafts. Creating smaller rafts and arranging them in parallel to the dominant flow path will improve overall nutrient removal.

Common themes and future work

The total number of published studies related to the functioning, modeling, and optimization of CSWs was similar in 2018 to the year before. Most studies fell in the categories of field studies, modeling, and design optimization. Multistage treatment or *treatment train* processes were a recurring theme in 2018, including several studies which examined how individual components such as sediment forebays, vegetation zones, and vertical sand filters improved overall performance of CSWs.

Bioretention

Bioretention refers to a low impact development (LID) practice in which runoff is temporarily stored in a depressed bowl—typically vegetated with a mix of grasses, forbs, shrubs, and/or trees—and infiltrated through underlying porous layers comprised of engineered media or native soils. Although certain nuances in design can be identified, the bioretention category herein has been extended to include similar LID practices of rain gardens, biofiltration, and infiltration trenches. There were 37 studies published in 2018. The following sections review experimental and numerical studies in which bioretention performance was quantified, followed by studies in which media enhancements or biological components of bioretention design and performance were examined.

Field, laboratory, and modeling performance studies

Two field studies were dedicated to understanding how bioretention systems perform on a long-term basis. A study to assess the long-term accumulation of heavy metals in bioretention systems showed that catchment type was an important determinant, with industrial sites having the greatest metal concentrations in the bioretention media and residential sites the least. Zn accumulated to the greatest extent across all sites (Al-Ameri et al., 2018). The development of engineered bioretention soils with time revealed podogenesis occurring within the first few years of bioretention installation. Plant roots, organic matter, and soil fauna were well established approximately 10 years after construction (Mitchell & Kangas, 2018). Pollutant removal performance in some cases did not improve with age (Flanagan et al., 2018).

The field performance of roadside bioretention systems showed that these systems were ideal for the treatment of particulate-bound pollutants (>90% removal; Flanagan et al., 2018). However, dissolved phase pollutants were treated poorly and in some cases export of nutrients was observed. The ability of a bioswale to treat polluted road runoff in terms of TSS and fecal indicator bacteria showed that water quality emanating from the underdrain of the system was significantly cleaner than the influent road runoff, both in terms of TSS and fecal coliform removals (Purvis et al., 2018). Nutrient export from roadside detentions was attributed by another study (Shrestha, Hurley, & Wemple, 2018) to high compost content in the bioretention soil with high rainfall events and inflow rates limiting performance. A carbon (C) budget developed for roadside bioretention systems in VA showed that the greatest pool of C was contained within the bioretention soil, a pool that exceeded C embodied by vegetation and the microbial community (Shrestha, Hurley, & Adair, 2018). The bioretention system as a whole was shown to be a net sink for nutrients. In another study that examined dissolved nutrient and greenhouse gas fluxes from a bioretention basin, the system was found to be a net source of nitrate, soluble reactive phosphorus (SRP), and dissolved organic carbon (DOC). Nitrate leaching was associated with a low C:N ratio in bioretention media (C:N ratio >20 recommended), while high P and C content caused SRP and DOC export (McPhillips, Goodale, Goodale, & Walter, 2018).

Denitrifying bacteria abundance in 23 bioretention cells was positively correlated with organic carbon and inorganic nitrogen in the media, with bioretention cells planted with grasses having the lowest denitrifying potential compared with other vegetation (Waller et al., 2018). The upper layers of the cell had higher concentrations of denitrifying bacteria compared with lower layers, despite the presence of saturated zones in lower layers that are generally meant to enhance the abundance of denitrifying microbes.

Several field studies examined the hydrologic performance of bioretention cells. Simulated increases in stormwater loadings to bioretention cells demonstrated that these systems could be an important ingredient in improving climate resiliency in terms of peak flow and volume mitigation (Cording, Hurley, & Adair, 2018). Runoff diverted into a stormwater infiltration basin was shown to only impact groundwater levels immediately downstream of the basin, with most infiltrated water taken up by transpiration in the summer months (Bonneau et al., 2018). The ability of residential rain gardens to manage stormwater volumes is dependent on the in situ soils that underly them to exfiltrate stormwater, as opposed to more engineered bioretention systems that utilize underdrains if the soils are poorly draining. A study of 11 residential rain gardens tested with a stormwater runoff simulator showed that the majority of the rain gardens were unable to manage a design storm of 3 cm, with the size of rain garden being the limiting factor, not the rate of infiltration (Anderson, Franti, & Shelton, 2018).

A laboratory study on planted and unplanted laboratory mesocosms (Wang, Zhang, Li, et al., 2018) showed an internal water storage (IWS) zone and a carbon source within the IWS significantly impacted removal rates. The mesocosms with IWS and carbon source outperformed those with IWS but without the carbon source, with respect to NO_3, NH_4, and TP removal. Removal improved with increased hydraulic retention time. Removal of metals (Cu, Pb, and Zn) all exceeded 93% regardless of IWS or carbon presence. The removal of metals from a graywater source (Chowdhury, Abaya, Tsiksi, & Mohamed, 2018) using planted bioretention columns showed that Zn (98%) and Cu (75%) had the highest removals, with Zn content in the soil accumulating to the highest extent over a six-month study. Microbial communities were most influenced by plant type in the upper portions of a column, while in the lower sections of the column they were most affected by the presence or absence of a saturated zone (Morse et al., 2018). The impact of a saturated zone on TN removal was demonstrated by demonstrating that TN removal was increased from 35% to 73% by increasing the saturated zone depth from 0 to 600 mm. NH_4^+–N removal however was invariant of saturated zone depth (Wang, Wang, et al., 2018).

A hydrologic model of a bioretention cell demonstrated that variability of media hydraulic conductivity in the vertical direction was most influential, with up to eight infiltration measurements needed to adequately quantify the overall hydraulic conductivity of the system (Kanso et al., 2018). Modeling the relationship between bioretention cell size on mitigating flow flashiness in downstream receiving waters showed that there was a maximum bioretention size beyond which no further benefits were accrued in terms of mitigating streamflow flashiness (Wright, Istanbulluoglu, Horner, DeGasperi, & Simmonds, 2018). The threshold cell size was greater in drier climates compared with wetter conditions. A similar study employed SWMM to model the performance of bioretention cells with differing areal extents and then creating a series of lookup curves to related performance targets with the required area needed for a bioretention cell. The results of the work showed that there was a nonlinear relationship between performance targets and bioretention cell area, and that careful evaluation of performance targets is critical to optimize bioretention cell area (Yang & Chui, 2018). A process-based model to describe the removal of microbes in stormwater by a bioretention system had predicted results that agreed well with observed data (Nash Sutcliffe: 0.46–0.68). Microbial adsorption, desorption, and die-off were modeled within three “buckets” of the bioretention system: ponding, unsaturated, and saturated zones (Shen, Deletic, Urich, Chandrasena, & McCarthy, 2018). An add-on module to extend the capabilities of the popular SWMM model was developed to simulate TSS removal by bioretention cells (Tiveron, Gholamreza-Kashi, & Joksimovic, 2018). The pollutant removal efficiencies of bioretention systems were quantified using three test systems with varying bioretention media, with the hydraulics of the system modeled with HYDRUS-1D to test parameter sensitivity. The parameters of influent concentration, media thickness, and inflow rate were shown to be the most important criteria governing overall pollutant removal performance of the systems (Li, Cao, et al., 2018; Li, Zhao, Li, & Chen, 2018). HYDRUS-1D was also used to simulate unsaturated drainage fluxes from a bioretention cell, with simulated fluxes then employed to calibrate a key parameter in the more commonly used SWMM v 5.1. This two-step process allows for the simulation of both unsaturated and saturated drainage conditions within SWMM (Lynn, Nachabe, & Ergas, 2018).

Enhanced media

Improvements to the removal of phosphorous were demonstrated through the incorporation of amendments to bioretention media through several studies. Removal efficiencies for TP and SRP were over 96% when a 10% amendment of water treatment residuals (WTR) was used (Li, Li, Dong, & Li, 2018). Adsorptive properties of WTR were also demonstrated with a 10% blend of WTR, with desorption of phosphorous back into effluent only after the equivalent of 15 years of influent water (Zhang, Li, Li, & Li, 2018). The removal of dissolved P from stormwater using high-flow media modified with alum and partially hydrolyzed aluminum (PHA) amendments showed that amending the media had significant improvements compared with unamended media; PHA amended media reduced P concentrations to less than 0.01mg after a contact time of one minute (Yan, James, & Davis, 2018). Fly ash mixed with sand was also shown to be effective in phosphorous and SRP removal (Li, Liang, Li, Li, & Jiang, 2018) with antecedent dry periods between loading events improving removal rates. The testing of high-flow media systems showed that coarse-grained sand filters are effective at removing particulate, and particulate-bound pollutants. These subsurface treatment systems have small footprints, are unplanted, and can be tied directly into stormwater catch basin outflows. They however performed poorly in terms of N removal (Landsman & Davis, 2018). The addition of nutrients to filter media comprising crushed clay and granular activated carbon was found to remove 50%–60% of the organic deicing compounds in influent stormwater, with the most active separation occurring in the top 20 cm of the filter (Raspati, Lindseth, Muthanna, & Azrague, 2018). A study that used an analytic hierarchy process to evaluate which of six types of media performed best over a range of pollutants found that a sandy clay media with the highest organic content (1.31% by vol) and lowest d_{10} (0.005 mm) ranked highest (Mei, Gao, et al., 2018).

Vegetation and other biota

A critical review of published literature related to the role of plants in bioretention systems showed that planted systems outperform the unplanted in terms of permeability and nitrogen removal. However, there was little evidence to support the common hypothesis that native plants effected superior treatment compared with exotic species, or that a diverse planting palette outperformed a system with fewer plant species (Dagenais, Brisson, & Fletcher, 2018). A two-species plant palette with deep fibrous rooting systems was shown to have better pollutant removal rates than a seven-species palette (Cording et al., 2018). Another review of published works related to the influence of vegetation on stormwater pollutant mitigation concluded that vegetation performs critical roles, roles that encompass the hydrologic, biogeochemical, aesthetic, and sociological realms (Muerdter, Wong, & LeFevre, 2018).

The study of tree species for use within bioretention systems was a recurring theme in 2018. An evaluation of substrate soil water content on evapotranspiration (ET) and drought stress (quantified as leaf water potential) in 20 species of Australian trees (Szota et al., 2018) showed that trees that can downregulate ET rates with drying soils were best suited to bioretention systems. Tree health in bioretention systems was also quantified using metrics that define tree morphometry in the southeast United States (Tirpak, Hathaway, Franklin, & Khojandi, 2018). Tree health was linked to its ability to survive in the somewhat unnatural conditions in bioretention, in terms of soil moisture, soil structure, and biogeochemical conditions in the growing substrate. The Bald Cypress (*Taxodium distichum*) was found to have the best health of the five tree species examined.

The ability to grow safe vegetable crops in a bioretention system that treated stormwater was tested in order to examine the potential for stormwater as a resource for urban agriculture (Ng, Herrero, Hatt, Farrelly, & McCarthy, 2018). The results from the study showed that while the vegetable crops did not compromise the removal of nutrients and metals from the stormwater in terms of bioretention performance, levels of Cd and Pb in the vegetables exceeded food standards guidelines.

The release of total phosphorous and orthophosphorous from nutrient-rich compost amendments to bioretention cells was shown to be mitigated by incorporating fungi into the wood mulch (Taylor et al., 2018). The work also illustrated the importance of allowing compost-rich bioretention media blends to leach nutrients and metals for at least a year before use in a stormwater control facility. Another study that looked at the impacts of fungi growth in nutrient export by bioretention systems showed that the lowest rates of phosphorous export were associated with mesocosms that incorporated mycorrhizal fungi, with TP reductions from 13% to 48%. Associated with the mycorrhizal fungi was improved uptake of copper and nitrate (Poor, Balmes, Freudenthaler, & Martinez, 2018).

Common themes and future work

The study of roadside bioretention field sites, the treatment of phosphorous, and the role of trees were some recurring themes in 2018. The potential for greater understanding of plant roots and root exudates as they relate to the microbial community, and for a more mechanistic understanding of how soil, plant, and microbial complexes effect pollutant degradation, was highlighted by Muerdter et al. (2018). The characterization of pore structure and hydraulic properties of 14 engineered media with varying compositions suggested that pumice-based media with pore radii of less than 1mm have complex water dynamics among and between aggregate particles (Liu & Fassman-Beck, 2018). These dynamics were not fully described by commonly used mathematical approaches and require further research.

Permeable Pavement

Permeable pavement systems have the potential to provide a variety of benefits, including stormwater volume and quality regulation, groundwater recharge, microclimate or heat island mitigation, skid resistance, and noise reduction. Over 30 papers were published in 2018 to describe one or more of these functional characteristics of permeable pavement systems. This body of work included two reviews. A state of the science highlighting permeable pavement systems and their application in the United States and parts of Asia and Europe was presented by Zhong, Leng, and Poon (2018). Their review placed particular emphasis on the importance of pore size distribution and connectivity on pavement hydraulic and mechanical performance, as well as the need to develop standardized mixing and testing procedures to better control these important structural characteristics of permeable pavement systems. A review of permeable pavement clogging mechanisms and methods for monitoring and modeling documented declines in system infiltration rate with age, indicating the need for ongoing maintenance (Razzaghmanesh & Beecham, 2018). The following sections present original research studies published in 2018 related to hydraulic and water quality performance.

Hydraulics and related properties

The majority of permeable pavement research published in 2018 was aimed to better understand the capacity for permeable pavements to mitigate stormwater hydrologic impacts, with 14 studies published in this topical area. At the laboratory scale, studies tended to focus on the relationship of pavement design, pore structure, and resulting hydraulic performance metrics. For example, the effects of aggregate size and type on pavement infiltration, permeability, and strength metrics were demonstrated by Grubeša, Barišić, Ducman, and Korat (2018), who found that coarser aggregate fractions generally enhanced hydraulic and strength properties, but that material type and geometry also played a role. While Grubešaet al. (2018) considered single aggregate sizes, Koohmishi and Shafabakhsh (2018) considered how the particle size distribution of graded aggregate influenced hydraulic conductivity and pore space. Similarly, they found larger pore sizes increased drainage rates and that flow was generally nonlaminar. Chu, Tang, and Fwa (2018) presented a suite of laboratory tests to evaluate drainage capacity in addition to skid resistance and tire-pavement noise and then demonstrated how the results of these laboratory-scale tests could be used to predict functional performance of an actual pavement system.

Multiple studies were also conducted to assess hydraulic performance of permeable pavement systems under field conditions. Rodríguez-Rojas, Huertas-Fernández, Moreno, Martínez, and Grindlay (2018) documented high reduction rates in stormwater volume and peak flow (median reductions >80%) and an increase in runoff lag time (median increase 70%–80%) for three pavement types (modular pavement, grass grid, and gravel grid) in Southern Spain. These systems were lined with an impermeable barrier, indicating the dominant volume loss pathway was evaporation (or evapotranspiration in the case of the grass grid system). Volume reductions ranging from 30% to 65% by a permeable interlocking concrete paver (PICP) system were observed during a monitoring study Seoul Korea (Shafique, Kim, & Kyung-Ho, 2018b). Rainfall intensity and depth in this study were up to 20 times greater than in the study by Rodríguez-Rojas et al. (2018), which likely contributed to differences in observed performance.

In addition to rainfall intensity, underlying soils may also constrain hydraulic performance of permeable pavement systems. Two studies demonstrated the potential to achieve runoff volume reductions despite low permeability of underlying soils. Braswell, Winston, and Hunt (2018) documented a 22% reduction in runoff volume via exfiltration and evaporation over a one-year monitoring period for a permeable pavement system installed over clay soils in Raleigh, NC. Volume reductions were particularly high (>70%) for events less than 8 mm in magnitude. Similarly, high volume reductions (16%–53%) were documented for three systems installed in Cleveland, Ohio, over subsoils with infiltration rates less than 3.5 mm/hr (Winston, Dorsey, Smolek, & Hunt, 2018). Incorporation of internal water storage zones was highlighted as a key design feature enhancing the hydraulic performance in both studies.

Clogging continues to be a major concern in permeable pavement systems and was the subject of eight studies in addition to the review by Razzaghmanesh and Beecham (2018). Maintenance, or a lack thereof, is a major factor in permeable pavement hydraulic performance through time. For example, Sañudo-Fontaneda, Andres-Valeri, Costales-Campa, Cabezon-Jimenez, and Cadenas-Fernandez (2018) found porous concrete and asphalt mixes were completely clogged after 9 years of operation without maintenance in an experimental parking lot in northern Spain. While a fraction of initial rates, infiltration into PICP systems at the same site was maintained at 3–16 m/hr over the same period, indicating that clogging processes are likely to differ with pavement type and their associated pore structures. The potential to maintain system performance through several different surface treatment technologies was demonstrated, though the authors of these studies note that the examined maintenance measures were only effective when continued on a regular basis (Sehgal, Drake, Seters, & Vander Linden, 2018; Støvring, Dam, & Jensen, 2018). Mechanisms underlying clogging are not yet well understood and are difficult to predict due to variability in pore structure and other design characteristics from one permeable pavement system to another. To better understand these clogging mechanisms, Hill and Beecham (2018) conducted a laboratory-scale clogging study and found that, in addition to bedding material type and depth, the order in which pavements were exposed to different sediment size classes influenced infiltration rates, with exposure first to coarse and then fine sediments causing the largest decrease in pavement infiltration. Kia, Wong, and Cheeseman (2018) also reported higher clogging rates when both sand and clay-sized particles were present. They went on to develop methods to characterize clogging potential, and presented three performance indicators (initial permeability decay, half-life cycle, and number of cycles to complete clogging) that exhibited strong correlations with one another and that could be incorporated in future service life models of permeable pavement systems. A field-based clogging study employing water content reflectometers and buried tipping bucket rain gauges revealed that the progression of clogging was controlled by rainfall intensity, location within the permeable paving system, and drainage area (Razzaghmanesh & Borst, 2018). Pavement hydraulic performance and clogging may also be tracked using standardized infiltration tests. The potential to supplement such infiltration tests with high-resolution images taken with a cell phone camera to track infiltration rates was demonstrated by Valeo and Gupta (2018). In an effort to observe clogging progression more directly, Zhang, She, et al. (2018) utilized image analysis of transparent sodium polyacrylate beads exposed to a stormwater mixture to track pore clogging with depth. They found the majority of clogging took place quickly (within 10 s of exposure to sandy sediment) and was concentrated in the upper 30 mm, though migration of sediment to depths of up to 100 mm was observed.

Modeling

Two studies presented models to describe permeable pavement hydraulic behavior. Guo, Guo, and Wang (2018) described an analytical probabilistic approach to better represent the dynamic nature of antecedent moisture condition (AMC) and capture its effects on hydraulic performance rather than assuming a constant AMC as typical of other models. Application of this model to four climatically different sites across the United States indicated AMC was near zero in most cases. They also note their approach could be adapted to obtain equivalent curve numbers or runoff coefficients for permeable pavement systems to assist with the planning and design of these systems. A numerical method (computational fluid dynamics or CFD) was used to examine the effects of pore structure and connectivity on seepage velocities and pressure gradients in virtual 3D permeable concrete structures (Zhang, Ma, et al., 2018). The resulting relationship between seepage velocity and pressure gradients was used to estimate hydraulic conductivity as a function of porosity.

Water quality

Changes in physical, chemical, and/or biological characteristics of water passing through permeable pavement systems were the focus of 11 studies published in 2018. These studies were conducted in the laboratory or field and generally focused on one or more of the following parameters: suspended solids, nutrients, metals, bacteria, or other organic materials. Filtration and sorption are the primary pollutant removal mechanisms in permeable pavement systems (e.g., Zhang, Yong, McCarthy, & Deletic, 2018). This collection of water quality studies generally reflects these mechanisms. The majority reported higher removal performance for particulate-phase pollutants relative to dissolved pollutants. For example, Braswell, Winston, et al. (2018) reported lower event mean concentrations (EMCs) for permeable pavement effluent relative to conventional pavements for a suite of stormwater pollutants with the exception of nitrate. Similarly, increased nitrate concentrations were observed in other monitoring studies, while concentrations of pollutants that tend to sorb to particles were observed to decline (Braswell, Anderson, Anderson, & Hunt, 2018; Hammes, Thives, & Ghisi, 2018; Zhang, Li, Zhang, et al., 2018).

Metal retention was the primary focus of several studies. Zhang, Yong, et al. (2018) developed the first permeable pavement sorption/desorption model to describe long-term metal retention capacity of porous pavement systems and tested this model with a year-long "accelerated" experimental dataset representing 26 years of pavement operation under variable hydrologic conditions. Model predictions fit experimental data well for Al and Cu and moderately well for Fe and Pb. With the exception of Mn, average removal efficiencies over the 26-year simulation period exceeded 65%, but generally decreased through time, particularly as pavements began to clog. Long-term (6 years) removal of 22 different metals by 3 different permeable pavement systems was documented in a field study conducted in New Jersey (Liu & Borst, 2018). With the exception of As, Cd, Pb, and Sb, effluent model concentrations remained below established ground effluent limits for all samples. Compared to permeable concrete and asphalt surfaces, drainage from a PICP plot tended to have higher metal concentrations, and Al and Fe concentrations exceeded recommended limits in 50% and 93% of PICP samples, respectively. Effluent metal concentrations measured by Thives, Ghisi, Brecht, and Pires (2018) for plot-scale permeable asphalt were on the same order of magnitude as those reported by Liu and Jensen (2018). Although observed metal concentrations generally did not exceed environmental limits, they were higher than measured in rainfall and stormwater runoff at the study site. Muthu, Santhanam, and Kumar (2018) and Zhao, Zhou, Zhao, and Valeo (2018) examined potential applications of permeable pavement systems for waste streams with relatively high Pb concentrations (8–10 mg/L) and found that effluent concentrations of less than 1 mg/L could be achieved provided adequate hydraulic retention time (facilitated by pavement systems with lower infiltration rates).

Three studies monitored fecal indicator bacteria in permeable pavement effluent. Selvakumar and O'Connor (2018) reported significantly lower *E. coli*, enterococci, and fecal coliform concentrations in porous asphalt pavement than in PICP or permeable concrete. They hypothesized this difference was due to the relatively basic pH of porous asphalt, which was processed with an alkaline emulsion, and the large, connected pores present in the PICP plot. Comparison of fecal coliform concentrations between two permeable asphalt systems monitored by Hammes et al. (2018) suggested higher removals were possible when a sand filtration layer was incorporated as part of the sub-base design. Correlations between *E. coli* and TSS removal in permeable pavement systems indicated filtration was the primary mechanism by which bacteria were removed (Abdollahian, Kazemi, Rockaway, & Gullapalli, 2018).

Innovations

Several studies aimed to improve permeable pavement environmental and/or structural performance. With respect to water quality enhancements, the potential to increase pollutant removal by placing a manufactured filtration device in series with PICP was examined (Braswell, Anderson, et al., 2018). In this case study, treatment enhancements were minimal due to high rates of subsurface exfiltration from the PICP system and surface bypass associated with PICP clogging, both of which limited the drainage volume delivered to the secondary filtration device. Huang and Liang (2018) documented efforts to improve removal of organic pollutants associated with vehicle exhaust, namely BTEX (benzene, toluene, ethylbenzene, and xylene), by coating permeable asphalt surfaces with activated carbon (AC). The results were promising, with AC-coated systems sorbing 6% to 51% more BTEX compounds than the conventional porous asphalt samples (Huang & Liang, 2018). Qin, He, Hiller, and Mei (2018) examined runoff retention and associated cooling benefits associated with a new type of paver block. The block itself was capable of holding 9.5 mm/m^2, and maintained surface temperatures that were 2–10°C cooler than traditional permeable pavers. Three studies focused on permeable pavement material composition and related strength and durability properties. Internal curing with prewetted lightweight aggregates was shown to improve permeable concrete strength and resistance to degradation related to shrinkage and freeze/thaw cycles, indicating this production technique should be adopted (Kevern & Nowasell, 2018). The potential to reduce the embodied energy content of permeable pavement materials by incorporating waste products was also investigated. Ho, Huang, Hwang, Lin, and Hsu (2018) replaced a portion of the cement mix in porous concrete with blast furnace slag and co-fired fly ash, and found optimal mixtures had up to 90% of the strength of conventional porous concrete mixes and had higher permeability overall. In another study, palm oil fuel ash was incorporated in permeable concrete mixes as a potential application in palm oil-producing countries. Metal retention improved up to 40%, as did overall permeability with incorporation of the palm oil fuel ash product; however, compressive strength and abrasion resistance decreased (Khankhaje et al., 2018).

Common themes and future work

Considerable effort to demonstrate and improve the performance of permeable pavement systems continues. Although this technology should be relatively easy to adopt in urban areas given its function as both a paved surface and stormwater control measure, clogging and, to a lesser extent, load-bearing capacity continue to be major impediments. The body of work published in 2018 reflects ongoing efforts to address these barriers by developing a better mechanistic understanding of clogging processes, and it is likely that similar work to understand processes and environmental conditions under which clogging occurs will continue. Work to advance permeable pavement modeling, such as application of CFD (Zhang, Ma, et al., 2018) and more process-based water quality models (Zhang, Yong, et al., 2018), will also likely continue to better understand how pavement material and pore structure—which can be highly variable among and within various permeable pavement systems—affect long-term hydraulic and water quality functions. These properties vary within and among different permeable pavement structures, which likely arises due to a lack of uniform production methods. Therefore, work to standardize the characterization and testing of permeable pavement systems will also likely continue to improve the implementation and operation of these systems in the field.

Green Roofs

In 2018, there were at least 33 articles focused on green roofs. Green roofs are an interesting approach to stormwater management which focuses on reducing the volume and peak flow of runoff by capturing water within substrates and evapotranspiration (ET) from plants all of which occurs on the rooftop.

Field, laboratory, and modeling hydrologic performance studies

Green roofs consist of several design variables and operate under a range of hydrologic conditions in different climates around the globe (Akther, He, Chu, Huang, & Duin, 2018). However, even well-controlled microcosm studies of varying substrates and vegetation treatments have trouble identifying statistically significant trends due to variability between replicates (De-Ville, Menon, Jia, & Stovin, 2018). As such, broad characterizations about optimal green roof design are difficult to make. However, there is a consensus that the substrate layer is a significant factor in green roof function. The thickness of the substrate layer has demonstrated a clear correlation with retention, in particular for small rainfall depths (Gong, Yin, Fang, & Li, 2018). In Beijing, China, modules of varying substrate depth and vegetation resulted in a reduction in peak flow between 30.8% and 85.4%. Although plant type varied, it was not found to be significant. In another study in Beijing, only substrate soil type and depth were varied (Gong, Yin, Fang, Zhai, & Li, 2018). This study found that substrate depth, hydraulic conductivity, and rainfall depth correlated with higher retention, demonstrating that both thickness and type of substrate are relevant.

Green roof performance is tied to hydrologic and climate drivers as well as the common definition of a rainfall "event." In two studies in Norway, the typical definition of an event as rainfall greater than 0.5mm with at least 6 hr of dry weather prior was questioned. This definition created long rainfall events with low intensity which translated into limited retention of stormwater (9%) for nonvegetated roofs (Hamouz, Lohne, Wood, & Muthanna, 2018). However, under these wet and cold conditions there were still significant delay and reduction in peak flows from rainfall events which can be significant when looking at systems close to capacity. A second study in Norway which looked at green roof modules with vegetation at four locations had similar rainfall retention between 11% and 30% annually and peak flow attention between 65% and 90% (Johannessen, Muthanna, & Braskerud, 2018). Several design parameters were varied including substrate depth, retention fabrics, slope, additional substrate materials, and water retention. There was little variability between modules at locations, with ET and time between events playing a critical role in event-based retention.

Schultz, Sailor, and Starry (2018) found green roof retention was significantly influenced by rainfall depth and antecedent dry weather period (ADWP) for a green roof configuration in Portland, OR, USA. For two different thicknesses of 75 and 125 mm, 23.2% and 32.9% of total rainfall were retained. However, the rainfall depth was only statistically significant for rainfall events between 5 and 10 mm, demonstrating similar behavior as the green roofs in Norway. The ADWP is an important parameter in green roof performance as it identifies the duration in which a green roof can reduce its current water content through ET. It is then not surprising that ET is an important parameter when determining green roof functionality (Feng, Burian, & Pardyjak, 2018). Plant type will impact ET; for example, drought-resistant plants such a sedum demonstrate statistically lower ET rates than plants which require greater water use such as grasses. In hot, subhumid Salt Lake City, USA, other critical parameters included air temperature, surface moisture, relative humidity, and solar radiation.

The preceding studies focused on identifying the role of various design parameters on small-scale "modules." However, the literature describes full-scale green roofs of various sizes and age as well. A retrofitted green roof was installed in Seoul Korea on a roof of 663 m^2 (Shafique, Kim, & Kyung-Ho, 2018a). Similar to module-based studies, the extensive green roof demonstrated variable retention between 10% and 60% depending on the intensity and duration of the rain event. Todorov, Driscoll, and Todorova (2018) collected performance data over 4 years for a 1,190 m^2 green roof in Syracuse, New York. No change was seen in water retention capacity over the four-year study of the 95-mm-thick green roof with impressive retention rates between 75% and 99.6%. This performance is attributed to the unique construction of the roof including varying slopes, extra storage capacity, and significant ET.

Abualfaraj et al. (2018) monitored the drainage from a 27,316-m^2 extensive green roof in New York City, USA. EPA-SWMM LID-GR was used to model the performance of the roof as measured by total runoff volume and event peak runoff. Generally, predictions were within acceptable ranges for green roof models, demonstrating an average of 77% of the water retained. In addition, the model suggests that increasing the substrate depth would improve performance as it was one of the statistically significant predictors of performance. Herrera et al. (2018) also explored the use of a model (integrated hydrologic model at residential scale, IHMORS), for the prediction of green roof performance in Santiago, Chile. The model was calibrated and validated using 1.8 m × 1.8 m modules. While the IHMORS can incorporate a variety of parameters into the model, it was found that better understanding of vegetation changes is needed as errors were greatest for modules with greater vegetation.

Complex models require information about every part of a green roof system. Bettella, D'Agostino, and Bortolini (2018) sought to model drainage flux under wet conditions but suggested the behavior of an unvegetated green roof systems can be characterized by an on-off threshold if sufficient information about each layer is known. ET for unvegetated systems is dependent on the ADWP and vegetated systems have different ET depending on water availability, suggesting that a more complicated model is necessary. One such model is the SWMM model coupled with a modified ET term and monthly correction factor proposed by Palla, Gnecco, and Barbera (2018). The model was tested on a catchment in Genoa, Italy, under single site and catchment-scale assumptions. At a single site, this method avoids overprediction of green roof performance and on the catchment scale it demonstrates even taking into account the correction factor a significant impact can be made from green roof installation. Proper estimation of ET was also a focus for Jahanfar, Drake, Sleep, and Gharabaghi (2018), whose model used a modified Penman–Monteith equation to better predict hourly ET. The model was calibrated on green roof modules (381 mm × 508 mm) with a mix of meadowland grasses and a depth of 200 mm in Toronto, Canada. Due to the role of water stress on ET rates, modified predictions for water-limited conditions have the most to gain from improved ET prediction, demonstrating improvement in the root mean square error and maximum absolute difference in the modules in Toronto.

Given the impact of climate on the performance of a green roof, it would be beneficial to know where green roofs can have the greatest impact. Hellies, Deidda, and Viola (2018) incorporated climate and three hydrologic factors into a model to predict green roof effectiveness: annual index of retention (IOR), index of retention for extreme events (IOR_{95}), and water stress index (θ). Ideal conditions for green roof implementation would be high IOR and low water stress. Overall, the best locations for shallow green roofs include much of North America, Europe, Kazakhstan, South Russia, and North China with a few spots in the southern hemisphere. When considering a deeper green roof, much of South America, Australia, and spots in southern India and Africa become viable options.

Water retention is not the only benefit of green roofs. They can also improve thermal performance of buildings (Piro et al., 2018). This impact is most significant in sunny summer conditions demonstrated by improvement in roof temperature between an insulated green roof (17.7°C) and a traditional roof (54.5°C) in Italy. The actual benefit of a green roof depends on the interests of the community in which it is implemented. Sangkakool, Techato, Zaman, and Brudermann (2018) utilized a SWOT analysis to determine the main factors which influence the implementation of green roofs in Thailand. The study utilized local experts to determine factors relevant to their community. The three greatest factors influencing green roof adoption were #1 lack of subsidies (threat), #2 urban heat island mitigation (strength), and #3 lack of skills and knowledge (threat). The three factors the experts felt were the least important were #14 Aesthetics (strength), #13 possible damage and leaks (weakness), and #12 social responsibility (opportunity).

Whether or not green roofs are financially viable is a complicated question. Teotónio, Silva, and Cruz (2018) developed a framework to analyze financial costs, economic gains, and socio-environmental benefits from green roofs at both the individual and community scales. Throughout the analysis, intensive green roofs had an intriguing trade-off, demonstrating high up-front financial costs but greater economic and socio-environmental benefits. When the potential for rooftop farming and access to recreational space are considered, the argument is compelling. Overall, there is evidence that replacing an aging roof with a green roof is a viable option.

Water quality and substrate amendments

Substrate type and water quality are inherently linked (Jennett & Zheng, 2018). Of particular interest is the observation of increased phosphate loads from green roofs which have been a consistent concern within the green roof water quality literature. Okita, Poor, Kleiss, and Eckmann (2018) conducted a study of two green roofs which were 6 months and 6 years old. Samples were collected and analyzed for various nutrients via HACH kits and Cu and Zn by atomic absorption spectrophotometry. While the roofs are considerably different, both demonstrated greater total phosphorus and phosphate when compared with a control roof. Todorov, Driscoll, Todorova, and Montesdeoca (2018) also saw a significantly higher TP and phosphate concentration from the green roof in Syracuse, NY, USA, which exceeded EPA freshwater standards.

Ferrans, Rey, Pérez, Rodríguez, and Díaz-Granados (2018) conducted a study of 12 different green roof modules over a span of 3 years. The runoff was monitored for a wide range of nutrients, trace metals, micropollutants, and general water quality parameters. The modules were found to be a source of pollutants for the majority of the tested compounds, and no water quality parameters were correlated with plant type. However, substrate type was correlated to phosphorus, nitrates, color, turbidity, and a few other trace metals. The impact of vegetation type, substrate type, and thickness on the performance of 900 mm square green roof modules in Shenzhen, China, was also explored (Chai et al., 2018). Vegetation type significantly influenced COD and substrate type, and thickness was found to significantly influence NH_4^+. The modified pearlite better controlled NH_4^+ due to the improved substrate layer ventilation which supported nitrifying bacteria. The modules only appeared to be a source of nitrate and not TP. Pęczkowski et al. (2018) also explored the impact of plant substrate type and thickness on water quality parameters (TN, NO_3^-, NO_2^-, NH_4^+, TP, and PO_4^{3-}). Water quality was tracked for the 1,000 mm × 2,000 mm modules as well as a control surface and direct rainfall. Statistically significant differences were found between the control surface and direct rainfall for total N and PO_4^{3-}, suggesting the roof itself may be contributing to the water quality.

The substrate material is often attributed as a source of Phosphate. Karczmarczyk, Bus, and Baryła (2018) performed batch and column experiments on different extensive and intensive substrates to determine the phosphate leaching potential of the materials. Batch tests included leachable phosphates using distilled water, TP determined through the addition of 1nHCl, and a leaching column with tap water. Overall intensive materials released greater phosphate and total phosphorus. Only the HCl and column tests showed correlation. Baryła, Karczmarczyk, Brandyk, and Bus (2018) also investigated the role of substrate using nonvegetated 0.5 m × 0.3 m modules. All substrates contained elevated phosphate concentrations, and these levels increased in the second year. It is assumed the phosphate came from the washed gravel and expanded clay aggregates investigated in the study.

Vegetation

Vegetation has a significant impact on ET which influences the performance of a green roof. Li, Cao, et al. (2018) utilized a randomized block design to explore the impact of two succulents and four grass species on the performance of green roof modules. Overall, a correlation was identified between shoot biomass, root biomass, and root depth with runoff reduction, water retention, and ET. The grass species had a greater impact generating more biomass and higher ET. Du, Arndt, and Farrell (2018) explored 20 shrubs from various climates in southern Australia as green roof vegetation. The goal was to identify which plants, if any, demonstrated drought resilience and high-water retention. Climate of origin was not a good predictor of shrub behavior, and no one shrub was found to fit this scenario. Each plant responded differently to water stress conditions some reducing ET and others producing less biomass under drought conditions. Azeñas, Janner, Medrano, and Gulías (2018) also found plants produced less biomass under water-stressed conditions. However, of the five plant species of interest for use in Spain, only one demonstrated a statistically significant difference.

Mature green roofs are frequently a mix of vegetation. MacIvor et al. (2018) explored the role of plant phylogenetic diversity which was found to have a statistically significant impact on minimum and average roof temperature. An increase in diversity was also shown to result in an increase in stormwater retention but no increase in ET. Within the study, no two roofs were the same even with 8 replicates, suggesting it is extremely important to include replicates in the experimental design of vegetation studies. Zhang, Szota, et al. (2018) also explored the impact of monocultures as compared to mixtures of plants. Eighteen 1.15 m × 1.15 m modules containing six various vegetation combinations and three replicates of each were studied. Four plants were explored in monocultures and mixtures and found monocultures of *Lomandra longifolia* demonstrated the best stormwater retention (10%–16% greater than other plants) and ET (33% greater than the lowest). Interestingly, while some plants behaved the same in monocultures and mixed cultures, *Stypandra glauca* had 50% greater shoot biomass in the mixtures but also hindered water retention due to the creation of preferential flow paths.

Common themes and future work

In 2016 and 2017, there was a heavy focus on integrating field and laboratory data with models to predict green roof retention. While this still occurred within the 2018 literature, there was a significant shift toward the role of green roofs as potential sources of phosphates in the environment and the role of substrate material in water quality. There remains significant variability in green roof performance as it pertains to water quality and ET. Two areas of potential areas for future work include substrate leachate studies as well as the development of water quality models for green roofs.

Rainwater Harvesting

Rainwater harvesting covers topics relevant to the collection, storage, and treatment of stormwater runoff. The stormwater runoff originates from building rooftops, terraces, courtyards, and other impervious building surfaces and may be harvested for onsite use. Stored water and treated water are used for irrigation, toilet flushing, laundry, and/or outdoor uses. There were at least 13 papers published in 2018 on rainwater harvesting that discuss the quality, design, optimization, economics, and ecosystem services of this practice within the context of broader stormwater management.

Quality

At least seven research articles in 2018 examined water quality in relation to rainwater harvesting to determine implications of using rainwater for various applications ranging from onsite toilet flushing to treatment to potable quality. A study performed in the district of Columbia concluded that advanced rainwater harvesting and continuous monitoring and adaptive control (CMAC) technology: (a) reduced discharges from a combined sewer system and a municipal separate storm sewer system during rain events and (b) provided harvested water applicable for reuse and potable water use reduction (Braga, O'Grady, Dabak, & Lane, 2018). The use of rainwater was evaluated in a research study conducted on the East African Rift Valley where high fluoride in both surface and groundwater has been a historic concern. The study found that the blending of rainwater with the region's natural water would provide an option to address the high fluoride issues. The proposal was to explore improving the area's overall water quality through dilution of the natural water with rainwater harvested from Kilimanjaro (Marwa, Lufingo, Noubactep, & Machunda, 2018).

When it came to identifying overall quality of rainwater harvesting projects, many focused on holistic evaluation of the project and the determination of a system that will provide appropriate overall quality for the region being evaluated. A comparative LCA of decentralized and centralized treatment systems to treat harvested rainwater to potable standards was conducted. The study examined a decentralized, point-of-use system that that was developed by RainSafe Water against a centralized system and used SimaPro 8.0 for the LCA. The results indicated that a decentralized rainwater harvesting system to subsequently produce potable water showed poor environmental performance metrics when compared to a centralized system, but that a greater dependence in the United Kingdom (location of study) on renewable energy sources would greatly improve the environmental performance of the decentralized system (Yan, Ward, Butler, & Daly, 2018). A study was conducted that evaluated green rooftops, concave green lands, and porous pavements in Beijing, China, that also coupled an integrated life cycle assessment into a multi-objective optimization model to determine the overall quality of a solution for the city. The boundaries used included construction parameters (e.g., material production and equipment production), operation and maintenance (e.g., chemical production), and end disposal. The optimization model was based on nondominated sorting genetic algorithm II. The study's results found that green lands provide the smallest impact values with porous pavements having the highest (Li, Huang, et al., 2018).

Reliability of a rainwater harvesting system was identified to be related to system parameters, such as storage tank sizes, through a stochastic modeling approach. The study examined different regions of the United States and showed that rainwater harvesting systems in arid regions are generally less reliable in terms of water supply than those in more humid regions (Guo & Guo, 2018). A study that examined four climatic zones across China determined that greater storage and higher demand fractions would be important for areas with less rainfall to provide higher stormwater capture efficiencies (Jing et al., 2018).

A research project evaluated the use of rainwater harvesting solar pasteurization treatment systems in South Africa and overall microbiological indicator analyses before and after treatment. Small-scale Phungamanzi^{TM} systems were installed in South Africa with samples collected from the rainwater tank before pasteurization and through the outlet of the system, and indicator organisms were cultured and qPCR used to detect and quantify rainwater pathogens. Results showed that Zn was the one anion and cation that had values outside national and international drinking water guidelines. Total coliform, *E. coli*, fecal coliform, and heterotrophic bacteria were beyond standards in the unpasteurized tank water. When exposed to a pasteurization temperature of at least 66°C, these indicator counts fell below drinking water standards. The organisms of *Legionella* spp., *Pseudomonas* spp., and *Salmonella* spp. were still detected following solar pasteurization treatment (Reyneke, Cloete, Khan, & Khan, 2018).

Design optimization

Research performed in 2018 included several studies on design improvements of rainwater harvesting systems. One study found that combining a standard rainwater harvesting system with a reuse component would make the use of rainwater more appealing but would increase overall system costs and complexity (Ennenbach, Concha Larrauri, & Lall, 2018). Another research study performed case studies to identify main water savings from rainwater, graywater, and hybrid rainwater–graywater systems using RainTANK modeling software. A yield after spillage algorithm was used to provide a more conservative estimate of savings. Results of modeling systems in Malaysia indicated that 90% of nonpotable water demand for toilet flushing, laundry, and irrigation would be met by domestic rainwater systems, while commercial systems met 43% of the demand (with overall reliability ranging from 35.5% to 52.5% and 11.2% and 22.1%, respectively). A hybrid rainwater–graywater system was most beneficial to both systems, with domestic systems reusing rainwater and meeting additional demand with graywater and commercial applications having an inverse setup (Leong et al., 2018).

Design optimization research also included tools for policy makers and planners to properly select the geographic locations and engineering design of rainwater harvesting systems. Research was conducted combining infrared spectrum imagery from National Agriculture Imagery Program (NAIP), LiDAR data, and GIS software, which quantified the potential for rainwater harvesting in Escambia County, Florida. This work indicated that 62% of households consumed less water than could be harvested and 38% consumed more water than could be harvested (Grant, McKinney, & Ries, 2018). A study of five cities around the United States, each of which had rainfall series approximated as Poisson processes, led researchers to derive a relationship from system characteristics (i.e., average water use rates, rainfall conditions, and sizes of contributing areas) to system performance (i.e., water supply reliability of rainwater harvesting systems; Guo & Guo, 2018). A study that examined four climatic zones in China to develop a water balance model to examine the performance of rainwater harvesting systems concluded that arid and semi-arid zones have higher stormwater capture efficiencies achievable with a greater ratio of average daily water demand rate to roof area, or a greater ratio of storage capacity to roof area (Jing et al., 2018).

Evaluation of urban stormwater harvesting sites and overall planning remain complex issues, and researchers continue to evaluate processes for appraising projects. Using Melbourne, Australia, as a case study, a multi-criteria decision analysis was employed covering nine performance measures that encompass economic, environmental, and social areas. The researchers found that by first developing a screening methodology based on GIS, they were able to determine alternative sites for stormwater harvesting and then could use the multi-criteria decision analysis to provide a ranking of the sites that included stakeholder preferences and evaluation of performance measures (Inamdar, Sharma, Cook, & Perera, 2018). A study was conducted where satellite imagery was used to examine the impacts of land cover change in Sharjah, United Arab Emirates, from 1976 to 2017 on urban flooding and rainwater harvesting. The study used multi-temporal Landsat satellite images and manual digitization of land features to examine land cover changes during this period. Runoff was estimated based on the US Soil Conservation Services (SCS) model, and rainwater harvesting potential was based on examination of rooftops, rainwater tanks, and filtration/infiltration trenches. Results showed that urbanization led to increases in flood extent in residential areas and that rainwater harvesting potential increased in kind (Shanableh et al., 2018). Rooftop rainwater harvesting performed in Arizona found that rooftop rainwater harvesting has potential to meet outdoor water demand in arid regions. To gain even better performance, desert landscaping and other best management practices can be coupled to reduce overall outdoor water demand. Similarity, it was determined that rooftop rainwater barrels can be effectively used to store significant monthly rainwater needs (Tamaddun, Kalra, & Ahmad, 2018).

Economics and ecosystem services

The economics of implementation, operation, and maintenance of a rainwater harvesting was incorporated into a few studies conducted in 2018. For example, a study of advanced rainwater harvesting in Washington DC compared cost of implementation and maintenance against other low impact development (LID) practices. Researchers found that to capture 3 cm of runoff from 0.40 ha of impervious area, a permeable solution would be the least costly, and a cistern system would be the most costly, but the former would require the most surface area (Braga et al., 2018). A comparison of a rainwater harvesting with and without a water reuse component found that a standard system in the southeastern portion of the United States would offset demand of other water sources in the area while a more expensive combination of rainwater harvesting and reuse was predicted in the remainder of the United States to meet water demand (Ennenbach et al., 2018).

Due to the variability of wet weather events, researchers are examining rainwater harvesting systems in concert with controlling downstream drainage systems and supplementing potable water supplies. Researchers created a model using R software that simulates three types of rainwater harvesting systems: a conventional system, a passive release system, and an active release system that includes real-time control. The model incorporated inflow end-use demand and baseflow restoration. The rainwater harvesting systems with real-time control performed better compared with the other alternatives in baseflow restoration and stormwater retention (Xu, Fletcher, et al., 2018).

A decision-making framework to evaluate stormwater harvesting sites factored in several costs within the framework including removal costs of pollutants (TP and TN) as well as capital and operation and maintenance costs to rank various alternative sites for stormwater harvesting based on various economic, environmental, and social criteria (Inamdar et al., 2018).

A study conducted on Beijing using integrated LCA and multi-objective optimization identified green lands would have the smallest life cycle impacts. The optimization results indicated that the economic cost would be approximately 66 billion RMB Yuan (Li, Huang, et al., 2018). An economical hybrid solution for domestic and commercial applications was researched in Malaysia, showing that improved performance and savings would be achieved if a hybrid domestic solution was primarily served by rainwater and topped-off by graywater while a commercial application would be most economical when led by graywater and supplemented by stormwater (Leong et al., 2018).

Common themes and future work

A large portion of the research published in 2018 examined the selection of rainwater harvesting sites, regions, and climates most appropriate for rainwater harvesting (or a specific strategy of rainwater harvesting). Research also focused on overall water quality, inclusive of indicator organisms and specific cations/anions, to improve harvested water up to potability standards. It appears these two topical areas will continue to drive future work. Scale up of rainwater harvesting systems is also anticipated, including case studies of larger scale projects.

Watershed-Scale LID Assessments

2018 began with a timely review outlining the state of the science regarding efforts to scale LID research from local to watershed scales to better understand the cumulative effects of multiple GSI systems on hydrologic and water quality processes in urban watersheds (Golden & Hoghooghi, 2018). Both experimental and modeling approaches are needed to enable such progress. The following sections review work published in 2018 in which watershed-scale performance of LID systems was assessed and/or optimized through experimental field studies or watershed modeling. The section concludes with a summary of the year's work to better understand socioeconomic factors that underpin the implementation of technical assessment and optimization knowledge.

Field assessment

Two studies were published in 2018 in which LID hydrologic performance was assessed at the watershed scale through experimental field studies. Woznicki, Hondula, and Jarnagin (2018) monitored surface runoff from three watersheds with conventional stormwater drainage infrastructure (0.8–1.2 Ha) and one with vegetated swales (5.3 Ha). Runoff response from the LID watershed was substantially less than that of the conventional curb-and-gutter watersheds, particularly for small events (<6 mm). The authors also noted that under more extreme events, physical watershed features such as soil type and shape may control runoff responses to a greater extent than GSI orientation. Additional insight to LID effects on groundwater recharge was provided by Bhaskar et al. (2018). While their study was observational in nature, the authors did find evidence of more rapid groundwater rise and recession in association with proximity to recharge facilities and landscape position (farther from a stream). In consideration of water table effects on built urban infrastructure, this study reinforces previous work suggesting that areas with high unsaturated thickness (i.e., low water tables) are less susceptible to groundwater mounding from focused stormwater infiltration, as are areas that are near to streams, which serve to dampen water table fluctuations.

Modeling assessment and optimization

Nineteen studies were identified in which hydrologic modeling tools were used to assess and/or optimize the performance of LID systems within watersheds ranging from less than 1 km^2 to over 3,000 km^2. At finer spatial resolutions, studies tended to focus on the effects of LID approaches to mitigate local scale flooding. Two studies focused on flood volume reductions for events ranging from 2- to 100-year annual return intervals following the implementation of various levels of green roofs (Ercolani, Chiaradia, Gandolfi, Castelli, & Masseroni, 2018) and rainwater harvesting and soil amendments (Itsukushima, Ogahara, Iwanaga, & Sato, 2018). Both studies indicated high (60% to 95%) runoff and overflow reduction rates could be achieved through LID approaches. However, hydrologic response metrics to increasing levels of LID implementation reached threshold values that likely reflected capacity constraints of existing flow conveyance infrastructure (Ercolani et al., 2018). Watershed runoff responses to a range of small to large storm events modeled by Garcia-Cuerva, Berglund, and Rivers (2018) also followed a nonlinear trajectory, with a combination of centralized and decentralized bioretention basins outperforming rainwater harvesting across all modeled storm event scenarios. Maragno et al. (2018) applied the curve number method to a high spatial resolution (0.25 m) land cover dataset to assess flood reduction potential of existing vegetated areas (i.e., urban trees and turfgrass) and noted a mismatch in the location and ownership of areas with high runoff production (private parcels) and areas with high flood mitigation capacity (public parcels). In contrast to the event-based modeling adopted in studies such as these, Hoghooghi et al. (2018) ran a spatially explicit hydrologic model (VELMA) over a continuous 3-year simulation period to observe changes in a broader suite of hydrologic responses (surface runoff, ET, and infiltration/shallow subsurface flow) to LID implementation scenarios in a 0.94 km^2 mixed land use watershed. Their study highlighted differences in the fate of infiltrated water among LID practices with strong versus weak ET mechanisms, as well as the need to consider the spatial location of LID practices to the watershed outlet and in relation to other watershed land uses. Studies assessing LID system performance at larger watershed scales (>100 km^2) also tended to focus on the potential for LID to mitigate flooding under extreme events. For example, Bai, Mayer, Shuster, and Tian (2018) employed spatial datasets and landscape metrics to examine spatial relationships between urban green spaces, imperviousness, and documented areas with chronic flooding at the city scale. Greater flood risk was associated with landscape patterns in which impervious areas and green space were developed as large but separate patches. Carter, Handley, Butlin, and Gill (2018) employed a similar spatial modeling approach to illustrate that, at the basin scale, green infrastructure within headwaters may provide important flood mitigating services to downstream communities and that these services often cross political boundaries. Thakali, Kalra, Ahmad, and Qaiser (2018) used climate models to generate future 100-year design storm scenarios, which were then input to a hydrologic model (SWMM) representing a 216 km^2 watershed in the Las Vegas, NV area. They found that aggressive implementation of permeable pavement and green roofs could reduce predicted peak flows by over 50% for this extreme event. Fu, Jang, Huang, Lin, and Yeh (2018) presented a cross-analysis of model spatial scales and demonstrated that, while LID approaches were found to reduce flood volume up to 10% for a 2-year recurrence interval, the effect for more extreme events (25- to 100-year) and at larger basin scales was nominal. In an ecosystem service-oriented study, Zhou, Shen, Woodfin, Chen, and Song (2018) applied the Integrated Value of Ecosystem Services and Tradeoffs (InVEST) model, a case study of green roof and permeable pavement adoption by the city of Corvallis, OR, to demonstrate potential gains in city-scale stormwater regulating and carbon sequestration benefits.

Nine of the studies presented optimization frameworks or decision support systems (DSSs) to assist in selecting, sizing, and/or siting LID practices. The majority of these studies presented objective functions in which network cost was minimized while one or more hydrologic performance metrics—namely peak flow and runoff volume reductions—were maximized at scales ranging from the sewershed (Eckart, McPhee, & Bolisetti, 2018) to city scales (Mei, Liu, et al., 2018). Optimization approaches applied in these studies included genetic algorithms NGSA-II (Azari & Tabesh, 2018; Eckart et al., 2018) and nonlinear programming (Sadeghi, Loaiciga, & Kharaghani, 2018). An extensive review of these and other approaches for optimizing the spatial location of LID practices was also published (Zhang & Chui, 2018). Optimizing watershed-scale LID performance may also require consideration of environmental justice and other social factors (Garcia-Cuerva et al., 2018). Christman, Meenar, Mandarano, and Hearing (2018) presented an optimization model framework in which biophysical and social factors were taken into account. The framework, which was applied to a case study in Philadelphia, PA, incorporated expert opinion on linkages between social factors and LID features through an analytical hierarchical process to incorporate environmental justice and community capacity factors alongside runoff quantity considerations. DSS studies published in 2018 employed a variety of methods, including meta-heuristic harmony search to select and site LID practices at the city scale (Paola, Giugni, Pugliese, & Romano, 2018) to curve number and land cover-based approaches at the neighborhood (Eaton, 2018) to housing development (Kazak, Chruściński, & Szewrański, 2018) scales. Regardless of the approach or scale of implementation, optimization and DSS studies indicated that combinations of LID practices employing a variety of hydrologic mechanisms (e.g., storage, infiltration, and ET) tended to produce the most cost-effective solution set for managing stormwater runoff.

Whether for assessment or optimization, hydrologic model creation is an involved process that requires extensive data collection and processing. To streamline the data collection process, Allende-Prieto, Méndez-Fernández, Sañudo-Fontaneda, and Charlesworth (2018) presented a framework to more effectively integrate spatial data with hydrologic model creation. In another application of GIS-based technologies to enhance LID planning and modeling, Xu, Schreiber, Lu, and Zhang (2018) presented a framework to reliably identify and inventory LID practices using spatial data to reduce the time needed to identify such practices in the field.

Implications to watershed-scale planning and assessment

The field and modeling studies reviewed in the preceding sections add to the body of knowledge needed to understand the technical and, to some extent, economic aspects of watershed-scale LID implementation. However, LID practices and the watersheds in which they are embedded are complex socio-ecohydrological systems, and as such, watershed-scale LID implementation requires understanding of broader social, institutional, and political contexts (Dobre, Vinke-de Kruijf, Moretto, & Ranzato, 2018; Goulden, Portman, Carmon, & Alon-Mozes, 2018). The following section summarizes studies published in 2018 that addressed some aspect of social and technical factors that underpin efforts to effectively implement LID at watershed scales.

In a case study of LID adoption in Israel, Goulden et al. (2018) conceptually organized drivers and barriers to watershed-scale implementation according to the so-called pillars of institutional theory—cultural-cognitive (want to change), normative (ought to change), and regulative (forced to change) factors. They found that drivers for LID adoption varied across stakeholder groups and in time. Such differences in drivers were also exemplified in other LID adoption case studies. For example, goals to reduce water footprints and/or address water scarcity drove LID adoption in Singapore, Berlin, and Melbourne (Liu & Jensen, 2018), while water quality-related regulative factors have driven adoption in cities such as Milwaukee, Philadelphia, Portland, and Baltimore (Hopkins, Grimm, & York, 2018; Liu & Jensen, 2018; McPhillips & Matsler, 2018).

As detailed by DeMasters (2018), increasingly prescriptive regulative factors pertaining to stormwater quantity and quality have certainly driven LID adoption in the United States; however, a purely regulatory environment can be accompanied by a lack of compliance enforcement and misunderstanding of ownership and maintenance responsibilities, which erodes the effectiveness of regulations requiring LID and/or other stormwater management practices (Burnett & Mothorpe, 2018). The effectiveness of other policy instruments, including outreach and incentive-based policies, can be effective compliments or alternatives to regulatory approaches, particularly when implementation on private property is needed to achieve watershed hydrologic targets (Lieberherr & Green, 2018). The potential to increase public acceptance of LID approaches (as well as indicators of normative and cultural-cognitive factors) through such policy instruments was demonstrated for residents in the Wabash Watershed of Indiana (Gao, Church, Peel, & Prokopy, 2018). However, as demonstrated by Shin and McCann (2018), the profile of households that are most likely to adopt or otherwise support LID approaches differs from those that do not support LID; therefore, gaining support for LID from broader urban populations will likely require targeting education and outreach to nonadopters (Maeda et al., 2018). As documented by Beery (2018) and Coleman, Hurley, Rizzo, Koliba, and Zia (2018), resident experiences related to flooding and extreme events can serve as a driver for house or neighborhood scale adoption, indicating the importance of communicating the results of modeling studies that consider LID system performance under extreme events (as several of the watershed modeling studies reviewed in the previous section did) to the public at large.

Regardless of the driver, broader adoption is dependent on the organizational and financial capacity of the initiating groups and is most successful when groups with greater financial capacities (e.g., central governments) support the activities of local nonprofits or other informal networks (Dobre et al., 2018; Qiao, Kristoffersson, & Randrup, 2018). Ongoing investments in LID practices are essential to ensure facilities are properly maintained. Erickson, Taguchi, and Gulliver (2018) presented a technically oriented review of maintenance and testing methods utilized for some of the most common LID practices, and highlight the need for regular preventative maintenance to ensure systems continue to meet hydrologic and water quality performance targets and to avoid more costly restorative maintenance measures. They also emphasized the need for additional research to document the costs of such maintenance, uncertainty in which has been cited by others as a potential barrier to broader LID adoption (Coombes, 2018). Though the net positive value of green infrastructure practices has been demonstrated through cost–benefit analyses such as by Nordman, Isely, Isely, and Denning (2018), uncertainty regarding the value of LID approaches still prevails as an additional barrier to uptake (Coombes, 2018). Several papers in 2018 sought to advance understanding of LID values. In a study conducted in Michigan, Nordman et al. (2018) incorporated broader environmental and social benefits (including water and air quality, flood risk reduction, carbon sequestration, and scenic amenity value) in a life cycle cost–benefit analysis and reported net values ranging from \$109/m^3 of water quality volume reduction for conserving natural areas to \$-47/m^3 for green roofs. A similar study was conducted in Illinois focused on quantifying the social, economic, and environmental impacts of LID at single home and neighborhood scales (Kim, 2018). Ashley et al. (2018) developed a valuation tool (Benefits of SuDS Tool) to facilitate such cost–benefit studies and also demonstrate that the potential uncertainty in such assessments can be quite large (e.g., 50% or more). In recognition of the need to formalize consideration of values such as these in stormwater planning processes, BenDor, Shandas, Miles, Belt, and Olander (2018) described an ecosystem service framework specific to LID practices and other stormwater infrastructure to facilitate consideration of broader values in stormwater management planning. A study by Castonguay, Iftekhar, Urich, Bach, and Deletic (2018) indicated that decision makers may be less likely to consider maintenance costs, let alone ecosystem service values, associated with stormwater management. Rather, they found that policy makers were more likely to base decisions on installation costs rather than annual or net present life cycle costs. While this result indicates additional work is needed to embed actual cost–benefit values in stormwater decision making, the modeling approach presented by Castonguay et al. (2018) demonstrates much-needed progress in developing models capable of predicting LID adoption on the basis of hydrologic, ecologic, and socioeconomic factors.

Common themes and future work

Studies published in 2018 pertaining to LID assessment, optimization, and implementation at the watershed scale indicate progress in these areas is being made, but that many technical and social challenges remain. From a technical standpoint, multiple papers highlighted the need for additional field studies to complement and validate watershed-scale LID models. In terms of modeling, selecting the appropriate spatial and temporal resolution of models intended to represent the cumulative effects of small-scale processes at the larger scale of watersheds remains a challenge. Nested watershed studies employing different modeling tools at differing levels of resolution and complexity such as presented by Fu et al. (2018) are one approach to address this challenge. Future models intended to assess watershed-scale influences of LID practices may involve coupling models with a strong LID hydrologic component (e.g., SWMM) with spatially explicit models in which biogeochemical processes represented more mechanistically (Hoghooghi et al., 2018). Many of the studies included in this review acknowledged that the benefits of LID extend beyond stormwater runoff regulation; thus, work to formalize consideration of broader ecosystem services in LID assessment, optimization, and decision making is likely to continue. This collection of studies also suggests that the greatest constraints to watershed-scale implementation of LID approaches are largely social and institutional in nature. Thus, future work involving collaboration among various disciplines—including but not limited to engineers, economists, social scientists, ecologists, and landscape architects—is essential.

Other

Several studies were identified that did not fall into one of the categories presented in the preceding sections but that warrant examination given their novel contributions toward advancing stormwater management. As summarized in the following sections, these studies document innovations in treatment trains, stormwater conveyances, and application of sensors and other "smart" technologies to stormwater management.

Stormwater treatment trains, or systems of LID or other stormwater management practices that operate in series, were examined in four studies at scales ranging from the parcel to the watershed. At the residential parcel scale, Voter and Loheide (2018) modeled changes in site water balances following the implementation of a series of "nonstructural" LID approaches that were characterized as "impervious-centric" (namely impervious surface disconnection) and "pervious-centric" (augmenting soil storage and infiltration capacity). Model predictions indicated that, while augmenting soil infiltration achieved the greatest runoff reductions overall, the effect was greater in combination with impervious-centric approaches. Reductions in surface runoff were largely diverted to deep drainage rather than ET, indicating limitations to fully restore predevelopment water balances in urban areas. Drapper and Hornbuckle (2018) monitored the effects of rainwater harvesting coupled with a belowground media filtration unit on runoff quality from a multi-residence area. The system reduced TSS, TP, and TN by 61%, 28%, and 45%, respectively, over a 4-year period without indication of filter breakthrough. A treatment train system termed the sequential sedimentation–biofiltration system (SSBS) was tested by researchers in Poland at scales ranging from the street (2.8 Ha) to the city (5.7 km^2). The street-scale system consisted of a sedimentation basin, a dolomite gabion covered with coconut mesh mat, and a retention basin with a small floating treatment wetland, with a total footprint of 425 m^2 (Jurczak, Wagner, Kaczkowski, Szklarek, & Zalewski, 2018). A similar series of treatment processes was employed in the city-scale SSBS, just at a larger scale (footprint of 1,040 m^2; Szklarek et al., 2018). Pollutant concentrations were effectively reduced in both systems, though the street-scale system achieved higher rates for TSS (86% vs. 61%), TN (72% vs. 46%), and TP (67% vs. 37%), potentially due to difference in influent concentrations.

Several studies reported on hydrologic and water quality performance of innovative stormwater conveyance designs. Winston, Powell, and Hunt (2018) monitored the hydrologic performance of a grass swale retrofitted with two rock check dams and found that this relatively inexpensive retrofit reduced overall runoff volumes by 17% while increasing hydraulic retention time (HRT) for storms up to 38 mm. Increased HRT is also likely to improve water quality performance; however, a trade-off in this case was excessive sedimentation which caused clogging and loss of vegetation that was ill-adapted to extended inundation. Three studies focused on regenerative stormwater conveyance (RSC), which refers to an open-channel system consisting of engineered pool and riffle sequences to control and treat stormwater through surface and subsurface processes. Cizek et al. (2018) traced deuterium isotopes in an RSC system to demonstrate outflow from the system mimicked both event and pre-event hydrograph flow components for modeled predevelopment conditions. Significant pollutant load reductions were also observed in this system. As demonstrated by Koryto, Hunt, Arellano, and Page (2018), subsurface microbial and sorption processes drive reductions dissolved pollutant forms. A CFD program (FLOW-3D) was applied to better understand how RSC design controls velocity and energy dissipation (Thompson, Hathaway, Hathaway, & Schwartz, 2018). The authors used the results of this study to recommend a minimum number and desirable length-to-width ratio for pools in RSC systems to improve future designs. Although it is not traditionally viewed as a stormwater treatment practice, growing investment in stream restoration has propelled growing efforts to quantify its water quality influence. Using a before-after–control-impact approach at both the reach and stream scales, Thompson, Pelc, Pelc, Brogan, and Jordan (2018) reported enhanced water quality function following stream restoration (which, in this case, entailed filling a degraded channel with course substrates and wood chips and installing rock weir grade controls) over a 5-year monitoring period. Significant increases in N, P, and TSS mass retention were observed at the reach scale; however, these changes did not propagate to a monitoring point 600 m downstream, which could be indicative of the scale of influence of stream restoration.

The last innovation included here was an open-source platform developed to facilitate real-time monitoring and control stormwater systems, from individual devices to watersheds (Bartos, Wong, & Kerkez, 2018). The platform, named "open storm," was applied to two case studies to demonstrate its potential application to detect and communicate flood hazards at the scale of roadways or other local areas as well as to control discharge from stormwater management systems to optimize their water quality and hydrologic benefits.

Common themes and future work

This collection of innovations is indicative of overall efforts to integrate stormwater management systems across urban landscapes—from the rooftop to the stream—and to identify and understand potential synergies as energy and materials flow through and between these interconnected systems. As demonstrated by Bartos et al. (2018), there is a growing space for sensors and other technologies to dynamically optimize system performance throughout its operational life, and future work to improve and exploit these technologies is sure to continue. Understanding of pollutant transformations and hydrologic function of RSC and stream restoration is still nascent, and based on promising results obtained in studies published in 2018, continued work to understand linkages between system design and function is needed.

Conclusions

In 2018, over 250 studies related to stormwater characterization, control, and treatment were published, demonstrating urban stormwater remains an active area of research around the globe. The studies presented here ranged from highly fundamental and focused on one critical aspect of SCMs, to field scale studies of performance, to holistic watershed-scale multidisciplinary assessments. Observations associated with stormwater quality and quantity show that through continual study researchers are refining models and starting to explore contaminants of emerging concern. Studies focused on individual SCMs also demonstrated a trend toward quantity and quality models, incorporation of GIS-mapping techniques, as well as continued field and laboratory study of the function of SCMs. The impact of vegetation (type and presence) on the performance of various SCMs appeared in several subsections of the review, suggesting that a better understanding of the role of vegetation is trending within the stormwater literature. As researchers work to incorporate more details and reduce uncertainty in models of SCMs, watershed-scale LID assessments clearly show a need to not only quantify the performance of the LID in terms of water quantity and quality but also explore the potential co-benefits, costs, and trade-offs associated with LID. This requires a continued push toward multidisciplinary studies of LID and SCMs at watershed, localized, and individual scales.

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