Water Environment Federation
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Urban stormwater characterization, control, and treatment

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Abstract

This review summarizes over 280 studies published in 2019 related to the characterization, control, and management of urban stormwater runoff. A summary of quantity and quality concerns is provided in the first section of the review, serving as the foundation for the following sections which focus on the control and treatment of stormwater runoff. Finally, the impact of stormwater control devices at the watershed scale is discussed. Each section provides a self-contained overview of the 2019 literature, common themes, and future work. Several themes emerged from the 2019 literature including exploration of substrate amendments for improved water quality effluent from stormwater controls, the continued study of the role of vegetation in green infrastructure practices, and a call to action for the development of new models which generate reliable, computationally efficient results under the physical, chemical, biological, and social complexity of stormwater management. © 2020 Water Environment Federation

Practitioner points

- Over 280 studies were published in 2019 related to the characterization, control, and treatment of urban stormwater.
- Studies on bioretention and general stormwater characteristics represented the two most common subtopics in 2019.
- Trends in 2019 included novel substrate amendments, studies on the role of vegetation, and advancements in computational models.

Key words

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

Introduction

Over the years, urban stormwater management has shifted away from simply flushing stormwater out of cities toward deliberate management of the watershed. It is now understood that effective stormwater control must include localized stormwater control measures (SCMs) to attenuate quantity and improve quality of runoff as well as consideration of the watershed-scale response to green stormwater infrastructure (GSI) and low impact development (LID). Although stormwater management is the primary technical driver of GSI implementation, the role of ecosystem services in generating public support and acceptance of SCMs should not be underestimated (Miller & Montalto, 2019).

The objective of this review is to provide an overview of the 2019 stormwater management literature. This review adheres to the structure of the previous four reviews, beginning with literature which characterizes general urban stormwater quantity (rainfall–runoff) and quality. This is followed by sections covering seven SCMs: erosion and sediment control, constructed stormwater ponds, constructed stormwater wetlands, bioretention, permeable pavement, green roofs, and rainwater harvesting.

After outlining specific control measures, the review looks to watershed-scale LID assessments as well as literature that falls outside of the subsections defined above. Finally, as this is the 5th annual review conducted by this team of researchers, the review concludes with general observations over the past five years and a concluding statement on trending topics from the 2019 literature.

General stormwater

Design of stormwater control and treatment structures can only be effective if they are designed with proper knowledge and assumptions about the influent stormwater quantity and quality. As such, this annual review begins with a summary of new literature related to the characterization of stormwater. In 2019, more than 42 studies were published characterizing the physical, chemical, and biological aspects of urban stormwater.

Quantity

The stormwater management model (SWMM) developed by the U.S. EPA is a common approach used by researchers for modeling of urban stormwater movement at watershed scales. SWMM was used to simulate flood events in an urbanized 3,978-ha catchment in Malaysia (Hasan, Mohd Razali, Ahmad Zaki, & Mohamad Hamzah, 2019). The catchment boundaries were delineated using digital terrain models from LiDAR data, IKONOS satellite imagery, and on-ground verification. After validation via a modified rational method, the model identified six areas which may flood under the 50-year storm, and therefore, modifications to the drainage system were suggested. SWMM was also successfully coupled with WetSpa-Urban to model stormwater runoff in the 6.13-km^2 Watermaelbeek catchment in Brussels, Belgium (Rezazadeh Helmi et al., 2019). The high-resolution model utilized a step to speed up calculations by 130%. Niemi, Kokkonen, Sillanpaa, Setala, and Koivusalo (2019) incorporated an open source adaptive subcatchment model to speed up modeling and automate the construction of a model (SWMM) applied to an 85-ha urban catchment in Finland. The adaptive subcatchment approach merges areas with similar land cover and a common outlet into a larger subcatchment. The resulting run time was approximately 10% of the time to run a full unadapted model, and the Nash–Sutcliffe efficiency (NSE) was above 0.9 for all but one event. The adapted model tended to underestimate flow volumes but predicted peak levels well compared to the unadapted model which overestimated volumes and peak flows. Calibration of any model can also be a time-consuming process. A nondominated sorting genetic algorithm-II (NSGA) was used for the autocalibration of SWMM applied to a catchment in Hyderabad, India (Swathi, Raju, Varma, & Sai Veena, 2019). The algorithm maximizes the NSE and correlation coefficient (CC) and minimizes the sum of squared errors (SSE) and percentage error in peak flow (PEP) to find the optimal calibrated parameters for a given rainfall event. The algorithm was used to calibrate eight models for eight rainfall events after which the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was used to select the best parameters for continuous modeling of the basin. The model generated appeared to be most sensitive to imperviousness, width of catchment, and depression storage.

Where data may be scarce, researchers are often creative in using the information available. Barszcz (2019) used a modified Marshall–Palmer relationship to estimate rainfall from readily available weather radar data of reflectivity and rainfall rate. The Marshall–Palmer model initially underpredicted rainfall totals, but once modified, the method did a fair job replicating rainfall totals of two local rain gauges. The rainfall was then used as input data to model stormwater flow in SWMM for a 55.2-km^2 urban catchment in Warsaw, Poland. The model generally produced errors between measured and predicted flow of less than 25%.

Although SWMM is the most common modeling approach, other models such as the dynamic multibasin hydrologic model HYPE are used (Tanouchi, Olsson, Lindstrom, Kawamura, & Amaguchi, 2019). In an effort to incorporate more detailed land use information into the HYPE model, the high-resolution EEA Urban Atlas (UA) was used in conjunction with the more commonly utilized EEA CORINE database in a test catchment in the small town of Svedala in southern Sweden. The model which accounted for imperviousness documented in the UA demonstrated more realistic results. However, “realistic” flood conditions are spatially variable and include unique phenomenon such as reverse flow. Wang, Kinsland, Kinsland, Poudel, and Fenech (2019) developed a model which allows for horizontal inflow and outflow based on surface elevation and instantaneous surface water depth of all grids within the model. Using 100-m resolution, the model was able to capture much of the spatial trends of flooding and reverse-flow phenomenon which occurred in the 2016 flood in Lafayette Parish, Louisiana, USA. As there are no constraints to the level of detail which the model can accommodate, a balance between computational demand and reliable results must be found.

Hydrologic models become computationally expensive with increasing resolution. Kim, Keum, Keum, and Han (2019) explored the use of the Second Verification Algorithm of Nonlinear Auto-Regressive with Exogenous Inputs (SVNARX) to learn the relationship between rainfall and overflow generated from the output of a calibrated model in SWMM. The approach, which also utilized a self-organizing feature map (SOFM), was tested on the 7.4-km^2 drainage area of Gangnam, Seoul, South Korea, producing a goodness of fit of approximately 80%. In a similar effort, a dynamic evolving neural-fuzzy inference system (DENFIS) with an online algorithm for the evolving clustering method was used to predict runoff from rain events in Malaysia and Australia (Chang, Talei, Talei, Chua, & Alaghmand, 2019). The DENFIS outperformed the autoregressive model with exogenous inputs (ARX), the Hydrologic Engineering Center—Hydrologic Modelling System (HEC-HMS), and SWMM. Models such as DENFIS should not replace mechanistic models but may have substantial use in regions with minimal or evolving data sets.

Mechanistic models are only as good as the conceptualizations which underly their construction. Runoff from a rainfall event can be generated when the precipitation rate exceeds infiltration (infiltration excess) or when precipitation volume exceeds the available storage (saturation excesses). Utilizing Green-Ampt infiltration, the preference for infiltration excess or saturation excess flow was shown to be dependent on two nondimensional ratios: the precipitation rate normalized by the hydraulic conductivity and the soil depth normalized to wetting front potential (Stewart et al., 2019). Utilizing multiple references and urban soil profiles from 11 cities across the United States, urbanization was found to generally increase the likelihood of an area to have saturation excess-induced overland flow during long-duration low-intensity storms. A heavily instrumented 4,300-m^2 field station, which doubles as a recreational park in Lystrup, Denmark, determined the primary contributors to runoff were from saturation excess in the topsoil and subsurface throughflow (Nielsen et al., 2019). This site-specific conclusion was supported by the fact that none of the rainfall exceeded the measured infiltration capacity of the topsoil.

Quality

Land use has an undeniable impact on stormwater quality. Connections between precipitation, discharge, and turbidity were explored in Oregon where watersheds with a higher degree of urbanization demonstrated quicker turbidity peaks (Chen & Chang, 2019). These watersheds also demonstrated clockwise hysteresis indicative of the arrival of turbidity peaks prior to discharge peaks. A second study in Oregon focused on sources of metal pollutants and found that Zn was positively correlated with the percentage of land cover and average curve number and negatively correlated with elevation and slope of the subcatchment (Chang, Allen, Allen, Morse, & Mainali, 2019). Although Cd and Cu were also tested, no additional statistically relevant relationships were found; this is not uncommon in water quality studies. In Singapore, analysis of 12 water quality parameters over multiple land uses determined statistically higher event mean concentrations (EMCs) of TOC and TSS in parkland compared to other land uses; other trends between land use and pollutants were not found to be statistically significant potentially due to the small sample size (Song, Qin, Qin, Wang, & Wong, 2019). Gnecco, Palla, and Sansalone (2019) also explored relationships between EMCs of metals (Zn, Cu, and Pb) and TSS among various land uses using a nonparametric analysis. Highway sites in the United States had statistically higher TSS EMC, while sites associated with terminal ports had more significant metals. Cu and Pb had greater affinity for particulate-bound fractions, but overall TSS did not track with many of the tested metals and therefore should not be used as a lone predictor of water quality.

In some cases, specific pollutant sources are the result of known anthropogenic activities which may benefit from changes in standard (best) practices. For examples, towns of similar demographic, economic, and land use metrics in St. Louis County, Missouri, which switched to the use of brine as a deicing agent, had 45% of the chloride load of towns which solely used rock salt (Haake & Knouft, 2019). Similarly, Taguchi, Carey, and Hunt (2019) observed a reduction in runoff volume of 42%–87% and significant reductions in nitrogen (55%–88%) and total suspended solids (44%–88%) when residential and commercial downspouts were disconnected from stormwater systems and directed to specified infiltration areas. Cases like the above are ideal; in many cases, the source of a pollutant may not be known. A nonpoint source of PCBs may have been discovered in a study of 209 PCBs in stormwater sediments from roadway sites across Maryland, USA. The non-Aroclor congener PCB-11 was detected in all samples including at high levels in a sample containing small yellow flakes, which when tested also had very high levels and appeared to be yellow traffic paint (Cao, Capozzi, Kjellerup, & Davis, 2019). Additional testing is needed to explore whether azo-type pigments such as those used in traffic paint are a nonpoint source of PCBs.

Increasing analytical testing capability and a potential reuse of stormwater have spurred much interest in the presence of less commonly tested stormwater pollutants. A review of the prevalence of microbial contaminants detected in stormwater indicates the need for treatment and proper risk assessment studies prior to reuse of stormwater (Ahmed, Hamilton, Toze, Cook, & Page, 2019). Schreiber et al. (2019) found evidence of *Escherichia coli*, *Clostridium perfringens*, *Campylobacter*, *Salmonella*, *Giardia* cysts, and *Cryptosporidium* oocysts in two residential catchments in Germany. *Escherichia coli* median concentrations were well above regulatory/advisory levels at 3.7×104 and 8.6×104 CFU/100 ml for the two sites. A 16-year study of fecal coliform levels in stormwater throughout southern Vancouver Island, Canada, demonstrated high concentrations of fecal coliform with annual periodicity and positive correlations with residential area, temperature, and antecedent dry period (Xu, Valeo, Valeo, He, & Xu, 2019). Given the length of the study, a positive test ratio was used to screen out the influence of the number of tests per month to account for nonuniform sampling. The influence of land use type on trace organic compounds in stormwater was explored in commercial and high-density residential stormwater in Wisconsin (Brown, Bell, Hogue, Higgins, & Selbig, 2019). Event mean loads (EMLs) correlated with precipitation, but EMC did not. In addition, the EMLs did not correlate with antecedent dry days supporting the hypothesis that the trace organic compounds are transport-limited but not source-limited. The results were scaled to the Madison, Wisconsin, USA, and modeled via WinSLAMM. Finally, Chen, Guo, and Ngo (2019) presented a review of pesticides in stormwater runoff noting that influential factors in the presence of pesticides include (a) characteristics of the precipitation, (b) properties of the pesticide, (c) patterns of pesticide use, and (d) properties of the application surface. Unique to pesticides is the intentional application of the chemical to the land surface such that incorporation into runoff is not unexpected. Therefore, the use of pesticides such as organochlorine, which demonstrate chronic toxicity, environmental persistence, and bioaccumulation, is of particular concern.

Sediment in stormwater control and storage facilities also contains pollutants which can have ecotoxicological effects. When tested for PAHs, Cd, Cu, Cr, Ni, Pb, and Zn, the sediment in three stormwater tanks in Kielce City, Poland, had consistently high levels of Zn (Sałata, Bąk, & Górski, 2019). Several locations had Pb and Zn levels above the probable effect level

(PEL), a threshold which aims to set a lower limit for when adverse biological effects may occur. A review of inorganic and organic stormwater pollutants found that 97% of ecotoxicity caused by stormwater runoff was due to the presence of metals (Brudler et al., 2019). In freshwater systems, 81% of the toxicity was associated with Cu and 9% with Zn, while in saltwater systems, Zn was the primary driver of toxicity. The role of eutrophication was also explored but found to be moderate when compared to other sources of TP and TN such as agricultural runoff. Pollutants in urban stormwater also present a human health risk if stormwater is reused without treatment. Ma et al. (2019) collected 40 buildup samples over 20 experimental plots in Australia and analyzed them for light and heavy PAHs and metals Al, Cd, Cr, Fe, Mn, Ni, Pb, and Zn. The buildup samples were then used to estimate the corresponding concentrations in stormwater to allow for the calculation of a Hazard Index and cancer risk for an individual assuming exposure similar to that of tap water. Buildup was found to correlate traffic volume, and therefore, a reduction in traffic volume could reduce pollutant concentrations and the potential for health risk.

A common phenomenon in the transport of pollutants in urban runoff is the first flush effect. A synthetic study of first flush effects under two rainfall intensities found that surface texture of different impervious microcatchments influenced the magnitude of the first flush effect (Al Mamoon, Jahan, He, Joergensen, & Rahman, 2019). Although TSS, TKN, and TOC demonstrated first flush effects at all sites, the occurrence of first flush for metals was less consistent with variability between sites and between pollutants at a single site. Ekanayake et al. (2019) used UV spectroscopy to detect first flush of dissolved organic carbon (DOC) in western Sydney, Australia, during 13 rain events. No correlation was found between flow rate and pollutant concentrations, but there were interpollutant correlations between DOC, TDS, and conductivity; NO_3^- and PO_4^{2-} ; and TSS and turbidity. Sampling in Shenzhen, China, also confirmed first flush events for TSS, COD, NH_4^+ and TP using the dimensionless cumulative mass curves over five rain events (Liu et al., 2019). Correlations between land use, pollutants, and rainfall intensity were explored via PROMETHEE-GAIA, and the residential road was found to be a major source of NH_4, COD, and TP.

Mechanistic models of first flush rely on the ability to properly model pollutant buildup and wash-off processes. Buildup is commonly modeled using a power function. Wei, Wijesiri, Jia, Li, and Goonetilleke (2019) found that the power function worked fairly well for particles <75 μm in size but larger particles needed a new coefficient to improve the performance of the model. A 41-day experiment of sediment buildup in Tianjin, China, determined that although the power function was appropriate for approximately 20 days, a double bell-shaped curve fit the data better (Wang, Huang, & Li, 2019). This was hypothesized to be due to site-specific extrinsic factors, such as street sweeping, wind, and particle distribution. In an effort to improve the prediction of the buildup process, a genetic programming (GP) approach was explored to develop buildup algorithms for TSS, TP, and TN (Zhang et al., 2019). The GP models outperformed traditional approaches but still struggled to predict buildup (max NSE of 0.54 during validation). Given the GP models for each pollutant were unique (i.e., nontransferable between pollutants), pollutant-specific buildup process models were recommended. Exponential wash-off process models also demonstrated pollutant-specific accuracy when attempting to model the wash-off of TSS, PO_4, NO_3, NH_4, TP, and TN for 126 events from 12 sites in Singapore. (Gaut, Chua, Irvine, & Le, 2019). The model worked well for TSS which also had a statistically significant correlation with rainfall depth. Although the exponential wash-off model was reasonable for TN and TP, it failed to capture the dynamics of the dissolved pollutants and also struggled with larger catchments with a mix of land use and less homogeneous response.

SWMM is also commonly used in water quality modeling efforts such as those in the Amman Zarqa Basin in Jordan (Al-Mashaqbeh & Shorman, 2019). After calibrating the hydrologic portion of the model, nonpoint sources of BOD5, COD, and TSS were simulated using a constant EMC. The results indicated stormwater runoff is a greater source of pollutant loads than treated wastewater in the basin. Tuomela, Sillanpää, and Koivusalo (2019) created a similar model in SWMM for a residential area in southern Finland which included constant EMC sources of TSS, TP, TN, Pb, Cu, and Zn. The use of EMC values from the literature versus local data combined with dilution effects during large simulated rainfall events was identified as likely contributing factors to the mediocre performance of the model. A similar result was found for a hybrid SWMM-MOPUS model used to predict fecal coliform concentrations in stormwater in Beijing, China (Hou, Chen, Chen, Qiu, Zhang, & Shen, 2019). The SWMM model had good hydrologic calibration and validation, but successful modeling of fecal coliform concentration was variable with better predictions at low and medium concentrations of fecal coliforms. Although SWMM is common, it was not the only model used. A FULLSWOF-HR model was developed to model TSS concentrations in a small urban catchment near Paris, France, using a metamodel approach (Hong, Liao, Bonhomme, & Chebbo, 2019). The metamodels were constructed and calibrated on different groups of rainfall in an effort to provide more customized performance. The first TSS peak concentration was primarily attributed to particle characteristics, while additional fluctuations were attributed to the amount of pollutant available (i.e., buildup). Uncertainty in parameters associated with buildup and wash-off processes was investigated in SWMM with sediment transport applied to two watersheds in Folsom, CA, USA (Gorgoglione et al., 2019). The model was determined to be extremely sensitive to changes in accumulation and disappearance rates, suggesting efforts to improve characterization of the buildup and wash-off processes are vital in mechanistic modeling of stormwater quality.

Some researchers have chosen to explore the use of machine learning for modeling of urban stormwater quality and first flush behavior. Random forest and regression tree methods were explored for the prediction of the mass of first flush ratio based on seven rainfall-related variables (Jeung, Baek, Beom, Cho, & Her, 2019). The random forest model outperformed the regression tree method, demonstrating a narrow range of prediction and reasonable prediction of the mass ratios for runoff volumes of 10% and 20%. PCA, CART, and random forest were also used in a study which looked to determine the importance of parameters which influence the occurrence of first flush as well as predict the occurrence (i.e., yes or no) of a first flush event (Perera, Mcgree, Egodawatta, Jinadasa, & Goonetilleke, 2019). Of the parameters investigated, the most influential parameter for predicting the occurrence of a first flush event was the rainfall depth, followed by maximum rainfall intensity. Liao et al. (2019) attempted to predict runoff events with high pollutant loads utilizing a storm flow pollution index model applied in Shenzhen, China. The prediction was based on COD data and used a Gaussian cloud distribution to capture trends, randomness, and dispersing extent of the data. A high pollution index was found for moderate rainfall due to the balance of wash-off and dilution processes. Finally, artificial neural networks (ANN) were employed as a predictive model for heavy metals in sediments in four catchments with varying land use in Kielce, Poland (Bąk, Szeląg, Sałata, & Studziński, 2019). The model did reasonably well for Ni, Mn, Zn, Cu, and Pb with less than 21% mean relative error, but struggled to predict Fe (mean relative error of 48%) and could not predict the occurrence of Co or PAHs without significant error. Catchment parameters such as land use exerted more explanatory power when compared to meteorological parameters.

Common themes and future work

Researchers continued to explore water quantity and quality topics in 2019 including progress in pollutants of emerging concern and health/ecotoxicity of stormwater. Heavy use of SWMM for both quantity and quality modeling continued along with mechanistic studies to refine our understanding of the underlying processes which drive stormwater runoff and pollutant buildup/wash-off processes. Unique to 2019 was an increase in machine learning models in both quantity and quality prediction, an area which is predicted to grow rapidly in the future.

Erosion and sediment control

Erosion and sediment transport result from changing environments (e.g., urbanization) and precipitation events. The former entails practices to prevent erosion over various landscapes, while the latter is associated with practices that manage sediment thus preserving downstream environments and ecosystems. There were at least nine papers published in 2019 on this topic.

Erosion control

Two erosion control studies focused on the efficacy of different materials for erosion control. Grushecky, McDonald, and Osborn (2019) explored the efficacy of certified composted wood chip media versus wood-run wood chip media in filter socks used for erosion perimeter control during oil and gas development activities. Screening was performed to determine physical characteristics of the chips and chemical analyses (i.e., nitrate, phosphorus, potassium, and conductivity). The researchers concluded that wood-run chips are applicable for use in all but the highest quality watersheds, with nitrate, phosphorus, and potassium values below regulatory requirements for both types of media. Water hyacinth fiber mats were explored for erosion control in Kajang, Malaysia. The testing apparatus included a soil bed with a 30-degree incline and rainfall simulator. Runoff samples were captured every 5 min and oven-dried, and particle sizes were identified. The mat provided an approximate reduction in soil loss of 83%, and researchers highlighted that larger particles eroded at the beginning of a rain event (Chow & Hashrim, 2019).

Auburn University has a center devoted to erosion control dissemination between academic institutions and industry practitioners. The researchers evaluated the Auburn University—Erosion and Sediment Control Testing Facility's training workshops to determine overall effectiveness in data sharing as well as overall reach of the program with the use of surveys to determine program quality in the eyes of the attendees. It was determined that there was a perceived knowledge gain of 54% by participants and that future efforts may include more take-home materials for future reference and potential certification (Perez, Zech, Donald, Turochy, & Fagan, 2019).

Sediment control

A watershed in the Miyun District of Beijing, China, was the site of research conducted to understand runoff and sediment yield. A regression equation was generated from data gathered from 2007 to 2016, including rainfall (via rain gauge and rain barrels), runoff, and sediment (measured in runoff plots). The most influential rainfall peak morphological index on runoff was peak width followed by peak number. The peak position had no significant effect on soil erosion, but it did have an effect on runoff (Xu, Zhang, Zhang, Li, & Wang, 2019).

The bedload sediment transport regimes of rivers with rural, urban with no stormwater management, and urban with peak-shaving stormwater management were the focus of researchers in Ontario, Canada. Metrics captured included water level, bed morphology (detailed topographic surveys), and sediment tracking (passive integrated transponder tags). The research found that the urban setting with no stormwater management resulted in frequent mobilization of sediments with larger materials' transport attributed to urban channel enlargement. The rural river's bedload sediment transport was associated with flood events (Papangelakis, MacVicar, & Ashmore, 2019). Researchers in Australia evaluated sediment budget based on the domains of hillslopes, built stormwater networks, and stream channels using bedload sampling traps and monitoring sediment yield in street-scale catchments. Regression modeling of different land cover types indicated that compared to forested catchments, hillslope erosion resulted in efficient sediment delivery (Russell, Vietz, & Fletcher, 2019).

Two ponds in Ontario, Canada, were used to evaluate sediment control at construction sites. The aim was to develop an empirical equation based on data gathered from the monitoring of two ponds and hydrodynamic (RMA2) and sediment transport (SED2D) modeling. Both ponds experience neighboring development with quiescent settling in the forebay of the ponds as the primary sediment removal mechanism. The researchers noted that reducing the length-to-width ratio in the model from 8:1 to 3:1 resulted in a 35% increase in effluent suspended solids (Binns, Fata, Ferreira da Silva, Bonakdari, & Gharabaghi, 2019).

Inspection and modeling

Modeling was done in the low Tyrrhenian coast of Italy to determine the change in net erosion over the previous five decades. Data such as daily rainfall and vegetation cover fraction were obtained from the National Hydrographic and Marine Service and GIMMS-KNMI Climate Explorer platform, respectively, from 1951 to 2000. With these data, a net erosion model was developed. The results highlighted that sediment fluctuations in the study area are attributed to climatic oscillations and that revegetation of land area reduces net soil erosion (Diodato & Bellocchi, 2019).

In an effort to support future study of erosion and sediment control, researchers designed a rainfall simulator using ASTM D6459-15 as a standard reference. The simulator included sprinkler heads, sprinkler risers, pressure gauges, and vessels. Testing was performed to calibrate the simulator and conduct bare soil control tests. The researchers were able to show that rainfall intensities of the simulator conformed to ASTM D6459-15, as did uniformity and consistency of droplet sizes (Ricks et al., 2019).

Common themes and future work

In 2019, the majority of published research focused on further understanding of the impacts of erosion and sediment practices. Future work appears to be headed to prevention and prediction. Given the ever-evolving landscape and environment, the ability to foresee erosion and sediment events would be of great benefit.

Constructed stormwater ponds

Research in the area of constructed stormwater ponds (CSPs) in 2019 covered topics related to water quality, biodiversity, and design and management of CSP for optimization. CSPs are a stormwater management technique that usually focuses on stormwater retention and detention. In many instances, the aim is to reduce peak stormwater flows that may arise from factors such as changing landscape in areas and/or urbanization and improve overall effluent quality. There were at least 23 papers published in 2019 on CSPs.

Water quality

A review of stormwater control measures was performed in 2019 that focused on nitrogen cycling processes. The review article highlights that denitrification may not be the only critical metric to monitor. The paper also highlighted gaps in knowledge including the connectivity between the nitrogen and phosphorus cycles, seasonal variability in stormwater control measures, and nitrogen fixation (Gold, Thompson, & Piehler, 2019).

A study conducted in Ottawa, Ontario, Canada, sampled two stormwater ponds at depths of 0.2 m and 1.5 m from June to August 2015 to better understand the development of hypoxic conditions and the related production of hydrogen sulfide. Hypoxic conditions generally initiated at the pond's maximum depth and migrated to the surface and, in turn, reduced water quality and resulted in the emission of hydrogen sulfide gas. CSPs with larger hydraulic retention times and depths may be more prone to hypoxia and hydrogen sulfide gas emissions (Chen, Delatolla, et al., 2019).

The transfer of microplastics from terrestrial areas into CSPs was published in at least two research articles in 2019 (Liu, Olesen, Olesen, Borregaard, & Vollertsen, 2019; Liu, Vianello, & Vollertsen, 2019). Microplastics (10–2,000 μm) were researched via seven ponds in Denmark spanning residential, industrial, commercial, and highway catchments. Samples were filtered using a 10-μm stainless steel mesh filtering device. The results highlighted the ubiquity of microplastics in all situations with land use as a differentiator in quantity and quality. The highest microplastic concentrations were identified in industrial and commercial samples, and the polymers identified included polypropylene, polyvinylchloride, polyester, polyethylene, and polystyrene (Liu et al., 2019). Related research conducted in Denmark focused on microplastic accumulation in the sediments of CSPs. Collected samples were analyzed using FTIR methods. The ponds hydraulically connected to industrial catchments produced the highest and lowest microplastic accumulations (127,986 μg/kg and 115 μg/kg) highlighting the importance of sediment accumulation when addressing the fate and transport of microplastics in CSPs (Liu et al., 2019). Research was conducted in Newmarket, Ontario, Canada, that also examined the impact of sediments within six stormwater ponds with a focus on phosphorus. Utilizing core incubation to characterize internal phosphorus flux rates and bioassay experiments, dissolved organic phosphorus was found to be ubiquitous in both the water and sediment of urban ponds, mobile, and released under various oxygen conditions (Frost, Prater, Scott, Song, & Xenopoulos, 2019).

Research was conducted in Minneapolis–St Paul, Minnesota, USA, which aimed to determine conventional and emerging contaminants in the sediments. Fifteen CSPs were used in the study (five each that are primarily associated with residential, commercial, and industrial land use) with sampling performed using a modified drop corer. Samples were taken of the upper 15 cm of sediment in the ponds. The results showed that commercial and/or industrial-related ponds had significantly ($p < 0.05$) higher concentration of Zn, 4-nonylphenol, brominated diphenyl ether, and total polybrominated diphenyl ether (Crane, 2019).

The impact of highway stormwater runoff in two overgrown dry detention basins was also a core focus of research in Raleigh, North Carolina, USA. The basins were monitored for approximately one year (January 2018 through January 2019) using Area Velocity Modules and automated sampling devices placed at the invert of each inlet pipe and at the outflow of the dry detention basins. Despite a lack of routine maintenance for nearly a decade, substantive runoff volume reduction (41% and 61%) occurred and reductions in ammonia, TP, and TSS were also documented (Wissler, Hunt, Mclaughlin, & Wissler, 2019).

Biodiversity

Thirty ponds of varying temporary and perennial water bodies in North Rhine-Westphalia, Germany, were selected to evaluate the impact of structural parameters, hydrologic parameters, vegetation cover, and landscape level on the conservation of odonates during the 2015 growing season. Results showed that ponds containing temporary water bodies were associated with species richness and exuviae density (Holtmann, Bruggeshemke, Bruggeshemke, Juchem, & Fartmann, 2019). A study conducted in Uppsala, Sweden, was performed to determine the relationship of adult dragonfly biodiversity and pond and land use variables such as area, age, conductivity, and shore vegetation. Thirty-one species of dragonflies were recorded from eighteen stormwater ponds. Species richness was related to pond area, and total vegetation cover and beta diversity components, determined using the Sørensen dissimilarity coefficient on presence–absence data, were correlated with percentage cover of floating algae scums and tall shore vegetation (Johansson et al., 2019).

Another study conducted in North Rhine-Westphalia, Germany, aimed to learn more about vascular plant species richness by comparing urban stormwater ponds and control ponds. Sampling included identifying the species richness with researchers recording 91 aquatic, 30 salt-tolerating aquatic, and 37 threatened plant species. Plant species diversity in the urban stormwater ponds was related to habitat heterogeneity that was provided via regular maintenance and the existence of terrestrial, semi-aquatic, and aquatic zones (Holtmann, Kerler, Kerler, Wolfgart, Schmidt, & Fartmann, 2019). Macroinvertebrate, zooplankton, and plant community biodiversity was also explored in twelve stormwater ponds in Norway. Samples were collected four times per year in both 2014 and 2015 using traps and a kick net. Pond size was positively correlated to the number of ponds within a 1-km radius and the taxa, with a significant positive correlation between the number of plant taxa and the number of zooplankton taxa (Sun et al., 2019).

A decrease in biodiversity downstream of stormwater outlets was discovered in Denmark despite no change in Fauna Index between upstream and downstream stations of pond outlets. The station measured various parameters including flow, Danish Watercourse Fauna Index, and sediment grain size. The researchers noted that negative impacts related to sedimentation and pollutant retention would have been worse if a CSP was not present prior to flow entering the receiving stream (Koziel, Juhl, & Egemose, 2019).

Design and management for optimization

The orientation and configuration of CSPs were shown to impact pond performance of CSPs in the coastal regions of the southeastern United States. A large single pond will perform differently under identical conditions compared to multiple, in-series ponds. This will ultimately impact the nitrogen and phosphorus cycle differently as sedimentation rates within the ponds highly impacted the amount of carbon and nitrogen sequestration via burial (Beckingham, Callahan, & Vulava, 2019). Ahilan et al. (2019) utilized the Revitalized Flood Hydrographs rainfall model and the layer-based hydro-morphodynamic model to model suspended sedimentological effects. Sediment trapping in ponds was more pronounced for frequent small- and medium-flow events with high variability in sediment trap efficiency. A 10-year maintenance cycle was recommended to account for deterioration attributed to remobilization of pollutants in the sediments.

Hydrodynamic modeling using the 3D Estuary and Lake Computer Model (ELCOM) was performed on three CSPs in Edmonton, Alberta, Canada, to examine the relationship between nutrients and eutrophication. The model required atmospheric stability correction and adjustments to albedo and light extinction coefficients to provide accurate predictions. To improve the model accuracy, future work on vegetated flow models was necessary due to the current models' inability to adequately represent densely vegetated areas (Nakhaei, Boegman, Mehdizadeh, & Loewen, 2019). The use of a hydrologic model to simulate runoff (HIDRO-FLU) and a hydrodynamic model to simulate basin operation (MODCEL) was used in a case study of a pond in Mesquita, Brazil, to determine the effectiveness and appropriateness of a CSP. The results showed that a CSP would be an efficient means of managing runoff volumes with the ability to provide approximately 80% peak reduction (Jacob et al., 2019).

The potential benefits of real-time control of CSP outlets were demonstrated using a conceptualized CSP modeled in SWMM with a four-dimensional dynamic system of passive, detention, on/off, and TSS control schemes followed by the use of the Monte Carlo method for failure analysis. The case study, situated in Milwaukee, Wisconsin, USA, showed that TSS control reduced system failure probability compared to on/off and detention control options and that TSS and detention controls settled greater amounts of solids relative to on/off control (Sharior, Mcdonald, & Parolari, 2019). Shishegar, Duchesne, and Pelletier (2019) also explored the use of real-time control of a CSP outlet via modeling with PCSWMM 7.0. The smart decision-making framework, which incorporates rolling horizon decision-making, optimized outflow set points to minimize peak flows during wet periods while also maintaining long detention times to optimize sedimentation and water quality. Modeled under future climate conditions, peak flow reduction varied with precipitation event between 73% and 95% with no overflow events, and detention times varied from 16 to 30 hr.

The design and effectiveness of micropools for stormwater detention basins were evaluated in Denver, Colorado, USA (Guo, Piza, & Mackenzie, 2019). Debris captured on a recently cleaned micropool outlet screen was collected after a wet weather event. It was determined that the micropool size should be based on debris particle float velocity, drain time, and capture volume as well as sediment dead storage time and evaporative losses.

The range and location of ice within stormwater retention ponds were the foci of researchers in Edmonton, Alberta, Canada. Direct measurements of ice thickness along with the use of ground-penetrating radar (GPR) were gathered from four ponds over the winter seasons of 2013–2014 and 2014–2015. The results showed that spatial variability of ice thickness increased following thaw events and that as the winter seasons progressed, ice thickness was less at restricted flow locations, inlets, and downstream of inlet basins (Kemp, Davies, & Loewen, 2019).

Floating static chambers for measuring greenhouse gas flux were used to examine fifteen CSPs in southeastern Virginia to ascertain greenhouse gas fluxes tied to anaerobic decomposition of organic matter in bottom sediments of the ponds. The two predominant gases during the summer were CO_2 and CH_4, both of which showed seasonality. CH_4 was the dominant greenhouse gas from unvegetated stormwater ponds, and the CH_4 flux was negatively associated with pond depth and surface area (Gorsky, Racanelli, Belvin, & Chambers, 2019). Forty urban ponds in Sweden were also surveyed to evaluate greenhouse gas emissions. Samples were collected to measure a range of parameters including dissolved oxygen, methane, and carbon dioxide. Researchers found that ponds with high nutrients (phosphorus and organic carbon) had greater methane concentrations and noted that artificial ponds may be an important component to consider when evaluating holistic greenhouse gas sources (Peacock, Audet, Jordan, Smeds, & Wallin, 2019).

The benefit of citizen scientists was on display in Scotland in assessing freshwater invertebrate groups in CSPs. The goal of the study was to determine whether the OPAL Pond Health Score, generated from citizen science assessments of pond health, was a useful assessment of overall ecological status of CSPs. The citizen science results were compared to researchers' ecological status assessment based on ponds' richness of amphibian species, general macroinvertebrate groups, and macrophyte species as well as richness of terrestrial habitats and degree of urbanization. Researchers found that the OPAL Pond Health Score was strongly correlated with measure of ecological status highlighting the value of citizen scientists (Rae, Miró, Hall, O'Brien, & O'Brien, 2019).

Common themes and future work

A large portion of the research published in 2019 focused on gaining better knowledge of maintenance and management of CSPs to find a balance in terms of intricacy of control and maintenance to maintain efficacy. Researchers also focused on studying the health of ponds by examining various populations such as invertebrate groups as well as the role of sedimentation on nutrient cycles and CSPs' performance. It appears that the topical areas of biodiversity, optimization, and water quality will continue to fuel researchers moving forward.

Constructed stormwater wetlands

In 2019, 17 publications focused on constructed stormwater wetlands (CSWs). CSWs 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 field, laboratory, and modeling studies, design optimization, and floating treatment wetlands (FTWs).

Field, laboratory, and modeling performance studies

Seven studies published in 2019 were identified in which the performance of constructed stormwater wetlands (CSWs) was assessed through laboratory, field, and/or modeling studies. Overall performance was assessed by Ventura et al. (2019) for a hybrid pilot-scale system consisting of a subsurface horizontal flow cell followed by surface flow cells. The system demonstrated exceptional indicator bacterial removal, reducing concentrations from 100 s to 1 s of colony-forming units (CFU) per 100 ml. Though highly variable, mean TN and TP removal exceeded 30%; however the authors suspected removal of the former was limited by internal N cycling and washout of algae and plankton. A deeper investigation of the mechanisms controlling N cycling in CSWs was presented in a set of companion papers from a research group at Monash University (Australia). Their work focused specifically on factors controlling relative partitioning between denitrification and dissimilatory nitrate reduction (DNRA) processes in CSWs by applying N isotope tracing methods to sediment slurries collected from four different CSWs. From a stormwater management standpoint, conditions under which DNRA may dominate are of interest since this presents a pathway through which NO_3 is cycled within the wetland to NH_4 rather than being removed from the system as gaseous N compounds (primarily N_2) via denitrification. Key findings from this set of studies indicated that: "Natural" organic carbon forms (as opposed to acetate) supported higher rates of both denitrification and DNRA (Rahman, Roberts, Grace, Roberts, Grace, Kessler, & Cook, 2019); DNRA was coupled to Fe^{2+} such that higher rates of DNRA were correlated with higher concentrations of Fe^{2+} (Rahman et al., 2019; Rahman, Roberts, Warry, Roberts, Warry, Grace, & Cook, 2019); a higher proportion of N was reduced through DNRA pathways when sediment temperatures fell below 12°C (Rahman et al., 2019); and while rates of both reduction pathways were inhibited by drying and rewetting cycles, DNRA was inhibited to a greater extent (Rahman et al., 2019). In all experiments, N reduction via the anammox process represented a very small percent (<0.05%) of total N reduction.

While research published in 2019 continues to support the adoption of CSWs to mitigate harmful impacts of stormwater quality on downstream ecosystems, CSWs do have potential drawbacks. Two papers investigated potential for greenhouse gas emissions from CSWs (Badiou, Page, & Ross, 2019; D'Acunha & Johnson, 2019). Both found that N_2O contributed negligibly to net greenhouse gas budgets, while mean CO_2 and CH_4 emissions ranged from 15.9 to 88.4 kg CO_2 eq/Ha/day. However, neither of these studies accounted for greenhouse gas offsets via carbon sequestration and/or accretion and burial of carbon sources from the watershed. Badiou et al. (2019) provided interesting insights into the role of emergent macrophytes in both carbon fluxes and overall water quality and concluded that increased TP and CH_4 export following emergent macrophyte removal warranted re-evaluation of vegetation removal practices in both CSWs and stormwater ponds. Hale, Swearer, Sievers, and Coleman (2019) summarized a series of experiments conducted in Melbourne, Australia, to explore the potential negative role of CSWs as "ecological traps" in which the fitness of biota attracted to the habitat provided by CSWs is compromised by habitat quality. Based on these findings, Hale et al. (2019) suggest management approaches to minimize adverse effects on resident biota by, for example, deliberately designing vegetation and other habitat features to attract biota to suitable habitat away from wetland inlets or other areas with higher pollutant concentrations.

Longer-term performance

Moezzibadi, Charpentier, Wanko, and Mosé (2019) examined changes in physical filtration functions of a vertical flow constructed stormwater wetland over a 5-year period using both piezometric head data and deterministic and stochastic modeling approaches. The filter layer's hydraulic response to wetting and drying cycles exhibited hysteresis effects, but also changed through time, likely in association with changes in vegetation biomass and root structure, deposition, and other characteristics of the filtration layer. To account for these dynamics, they presented an inverse modeling approach by which hydrodynamic model parameters of CSW sediments could be identified for successive wetting and drying events through time to improve model fits to observed piezometric heads.

Design optimization and innovations

General recommendations to optimize constructed urban wetland performance were provided by Ahn and Schmidt (2019) and included microtopography (e.g., by disking or incorporating other construction practices to increase surface roughness and heterogeneity), plant diversity (e.g., by intentionally planting a diverse plant community), and hydrologic connectivity to pollutant sources. Another important optimization factor identified through CSW studies is hydraulic residence time (HRT). The potential to optimize flow path and HRT in vertical CSWs with the use of vertically oriented baffles to improve nutrient removal performance was demonstrated by Chai, Li, Shao, Li, and He (2019). A modeling framework to better predict HRTs specifically as affected by wetland vegetation was presented by Sonnenwald, Guymer, and Stovin (2019). They demonstrated the potential to accurately represent mixing effects and resulting HRT distributions in vegetated CSWs and, by implementing the model framework within a commercially available CFD (ANSYS Fluent-19), the potential to adopt their method as a practical engineering planning tool to predict effects of vegetation patch density, distribution, and system geometries.

Floating treatment wetlands

FTWs are generally constructed of a thin buoyant mat that supports the growth of macrophytes, whose roots extend below the mat where they can access dissolved nutrients in the water column, which is deployed in ponds or shallow areas of open water bodies. While research in FTW for treating stormwater is still nascent relative to CSWs, the growing body of FTW knowledge stimulated two review articles in 2019. Both reviews focused on field-scale applications of FTWs. Bi et al. (2019) provided a broad overview of pollutant removal mechanisms and reported removal rates for a wide variety of compounds, and conclude that additional work is needed to understand how treatment efficiencies and other ecosystem effects mediated by FTWs may respond to changes in climate and pollutant delivery. Lucke, Walker, and Beecham (2019) presented a set of recommendations to improve robustness of experimental designs employed for monitoring the performance of FTW stormwater studies based on a review of eight existing field studies. These included designing monitoring studies as a before–after/control–treatment design; characterizing HRTs before and after FTWs are installed; quantifying nutrient uptake in plant biomass above and within the floating mat by sampling plant tissues at the start and end of each growing season; and arranging FTWs to minimize short-circuiting.

Pollutant removal performance by FTWs is strongly linked to vegetation and, as indicated by two studies published in 2019, to species-specific traits. Tharp, Westhelle, and Hurley (2019) demonstrated correlations between P uptake and root biomass and surface area. Similarly, Schück and Greger (2020) linked heavy metal removal with root traits (namely fine root biomass) as well as other plant traits (biomass and transpiration) based on a laboratory study of 34 wetland plants, particularly over short time frames (<0.5 hr). The authors developed a series of regression models for predicting metal uptake rates by FTW vegetation as a function of these traits. Regardless of species, the overall contribution of direct plant uptake may be modest, though nontrivial, relative to other pollutant removal pathways. For example, Zhang et al. (2019) attributed just under 8% of total N removal to direct uptake in a FTW system, while the remainder was attributed to microbially mediated denitrification, a process which is likely facilitated and enhanced by FTW vegetation. Survivability is another essential characteristic to consider when selecting vegetation to promote pollutant removal by FTWs, particularly in cold climates. In a comparison of four wetland plant species adapted to traditional CSWs in the region, Tharp et al. (2019) found clear differences in winter survival and resprouting rates after overwintering on FTWs, indicating that some species are better able to handle environmental extremes apart from the buffering effects of wetland sediments afforded to vegetation in a traditional CSW.

In addition to plant species and associated structural characteristics, water depth is also likely to influence nutrient removal performance in FTWs. For example, declining pollutant uptake performance was observed when water column depth exceeded 35 cm (Abbasi, Xie, Hussain, & Lu, 2019).

Common themes and future work

Among the most attractive features of constructed wetland systems for stormwater treatment is the capacity of these systems to "self-design," that is, the capacity for wetland plant, microbial, and other ecological components to adapt to changing environmental conditions. Nearly every study reviewed indicated these ecological components play an important role in pollutant transformations and/or removal in CSW systems. Many also provided insights into how ecologically mediated pollutant removal processes may change in response to environmental variables such as temperature (e.g., Rahman et al., 2019) and wetting and drying cycles (Moezzibadi et al., 2019; Rahman, Grace, Grace, Roberts, Kessler, & Cook, 2019) pointing to the need to consider how water treatment and other services provided by CSWs may respond to changes in climate, rainfall and drought patterns, and associated shifts in modes of pollutant delivery.

Clearly, there is still room to optimize or otherwise enhance the performance functions of CSWs. For example, incorporating baffles (Chai et al., 2019) or optimizing FTW placement (Lucke et al., 2019) to minimize short-circuiting, and advancing understanding of vegetation and other wetland complexities on HRT distributions through advances in modeling (Sonnenwald et al., 2019) indicated these systems can be further optimized through engineering design. Additional understanding of the role of plant functional traits and survivability in CSWs, as well as their role in attracting animals and other biota and cycling carbon, can also lead to selection of optimal "planting pallets" to jump-start the self-organizing capabilities of CSWs. While optimizing CSWs with respect to water quality performance has been and likely will remain a focus of the research community, the broader challenge arising from the work published in 2019 is that of integrating water quality functions within the broader context of ecosystem services provided by CSWs—including as an important albeit suboptimal habitat in urban areas and their roles in sequestering and emitting greenhouse gases.

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 55 studies published in 2019. The following sections review experimental and field studies, media enhancements, and biological components of bioretention design and performance. Included this year are a few relevant synthesis papers.

Field, laboratory, and modeling performance studies: *field studies*

The hydrologic performance of a single bioretention basin in a subtropical climate showed that over 29 events measured over two years, an average of 65% of runoff volume diverted to the basin was retained (de Macedo, do Lago, Mendiondo, & Giacomoni, 2019). The bioretention basin in Brazil showed retention rates of 73% and 61% of total runoff during the dry and wet seasons, respectively. Antecedent soil moisture conditions in the system drove dry season performance, while total rainfall and rainfall intensity drove wet season performance. In a follow-up study by de Macedo, do Lago, and Mendiondo (2019), outflow water quality was determined to be within Brazilian guidelines for water reuse in terms of NO_3^-, NO_2, Zn, Mn, Cu, and Cr. The authors suggest this demonstrates the potential for storage and reuse of bioretention outflows as a secondary nonpotable water source in dense urban areas. A rain garden in a high-density area in New York that intercepted street runoff retained 78% of all inflow volume, with 100% of retention of storm flow volumes associated with 26 rainfall events less than 10 mm (Feldman, Foti, & Montalto, 2019). The authors make the case that by retrofitting just 4% of the green space with green infrastructure, a 10% lowering of storm flow might be achieved. Two suspended pavement systems containing unlined subsurface bioretention systems demonstrated an alternative methodology to effect bioretention treatment of stormwater in ultraurban areas where space available for stormwater treatment is limited. The two systems captured over 88% of all runoff directed to the systems. Pollutant concentration reductions measured at one of the pavements showed a significant reduction in TSS (Tirpak, Hathaway, Franklin, & Kuehler, 2019). A field study comparing hydrologic and treatment performance among three types of urban restoration practices—three bioretention cells, three reconstructed native landscapes (reconstructed prairie), and two urban riparian buffers—determined bioretention cells had the highest infiltration rates, time to runoff, and the greatest accumulation of pollutants (Karnatz, Thompson, & Logsdon, 2019).

A study of two roadside biofiltration systems in France reported that particulates were removed from influent road runoff; however, poor filtration possibly due to preferential flows yielded high particulates over three winter storms (Flanagan et al., 2019). Over a total of 19 storms measured, the concentrations of dissolved trace metals (Cu and Zn) were correlated to dissolved organic carbon concentrations in the effluent. Dissolved constituents were not effectively retained in the biofilters. The removal of plastics, PCBs, and metals was examined over 5 years in an underdrained bioretention cell along a transit corridor in San Francisco Bay, California, USA (Gilbreath et al., 2019). Microplastic particles were reduced from 1.6 to 0.16 particles/L, and the concentrations of PCBs, Hg, and Me were greatest in the top 10 cm of the soil profile. PCB accumulation in the upper soils close to the inlet was at high enough concentrations that the top layer of soil would need to be replaced once every 8 years in order to meet screening concentration for residential and industrial soils. Two rain gardens in China studied over a period of two years to estimate the accumulation of soil N, P, and TOC showed that soil TN and NO_3-N decreased over the period of study, while NH_3-N and TP increased. In terms of vertical stratification, NH_3-N decreased with depth, while NO_3-N and TP increased with soil profile depth (Guo, Li, Li, Li, & Li, 2019).

A bioretention cell constructed over 17 years ago in North Carolina, USA, was evaluated in terms of its ability to remediate N and P. Data collected 10 months after construction (2002–2003) were compared with data collected in 2017–2018. The TN load reductions increased from 40% to 72%, while TP load reductions increased from 65% to 79%. The top 20 cm of the bioretention media was close to phosphorous saturation (Johnson & Hunt, 2019). Carbon stocks measured in 25 bioretention cells in Australia showed that the most C accumulation occurred in the upper 20 cm of the system, with around 32% of all C in the system limited to the top 5 cm (Kavehei, Jenkins, Lemckert, & Adame, 2019).

Field, laboratory, and modeling performance studies: *laboratory studies*

A study on the effect of freeze–thaw cycles conducted on laboratory columns of bioretention soils showed greater macropore formation and pore connectivity in columns exposed to freeze–thaw cycles, compared with soils in columns maintained at room temperature (Ding, Rezanezhad, Gharedaghloo, Van Cappellen, & Passeport, 2019). To ensure the survival of plants in bioretention systems that are exposed to prolonged dry periods, Barron et al. (2019) studied the performance of laboratory-built biofilter columns exposed to both stormwater and graywater which can be a good source of moisture for plants during dry weather. Eight species of plants with and without a mulch bed as a carbon source were exposed to intermittent dosing of stormwater and graywater. The study concluded that these dual-model filters were effective in treatment of TSS BOD5, TOC, DOC, and some heavy metals, and that plant survival was generally good. The effective removal of nitrogen and phosphorous was also possible with a careful selection of plant species. A column-based laboratory study to evaluate alternative flow pathways in bioretention systems was tested by Zhang, Sang, Sang, Che, and Sun (2019). Up-flow and mixed-flow systems were compared with traditional down-flow systems using a synthetic stormwater blend. The study showed that TN removal was 41% ± 23% for the up-flow system, 31% ± 16% for the mixed-flow system, and 17% ± 13% for the conventional down-flow system. There were no significant differences in TP removal.

Several laboratory studies examined the importance of internal water storage zones (IWSZ) in the treatment of stormwater pollutants. The importance of plants and IWSZ in promoting N removal was highlighted in an evaluation of 15 bioretention columns dosed with synthetic stormwater (Li, Yang, Yang, Davis, & Liu, 2019). Results showed that the presence of plants and submerged zone was associated with higher removals of TN and NO_3-N, and the control unplanted systems without submerged zones exhibited NO_3-N export. NH_4-N removal exceeded 95% across all treatments regardless of plant or submerged zone presence. Chen, Liu, Liu, Zhang, and Sun (2019) characterized nitrogen removal processes in bioretention columns and showed that nitrification and denitrification rates decreased with soil depth, while nitrification efficiencies were 3.4–4.4 times greater than denitrification efficiencies. Fan, Li, Wang, Huang, and Luo (2019) constructed a budget for nitrogen species in four laboratory-scale bioretention column setups with two flow patterns and two plant species, ultimately choosing one setup with the best performance for further analyses. The authors showed that on average 60% of influent TN was removed through plant assimilation and denitrification, while 36% was retained in the column, and only 4% left the system in the effluent. They also showed that most NH_4-N was retained in the soils, while NO_3-N was retained in the IWSZ of the column. In a study of *E. coli* removal associated with planted bioretention systems with IWSZ, *E. coli* removal was better in the planted systems compared to unplanted controls (Chandrasena et al., 2019). However, depletion of water in the IWSZ through plant transpiration following prolonged dry periods led to lowered *E. coli* removal efficiencies.

The adsorption and desorption of benzotriazole in bioretention systems were evaluated by Rhodes-Dicker and Passeport (2019). Benzotriazole is a corrosion inhibitor commonly found in antifreeze and deicing products. The chemical is toxic to aquatic ecosystems at high concentrations and has been associated with road runoff in cold climates possibly from road-deicing products. Through a series of batch adsorption and desorption isotherm experiments, the authors showed that under the limited conditions tested, bioretention system is likely to remove benzotriazole from road runoff through adsorptive processes. Column studies with intermittent flow and varied loading conditions are suggested as next steps. An investigation of three bioretention boxes constructed in a laboratory in Beijing University, China, to characterize nutrient and metal cycling showed that cumulative nutrient loads were removed to an 87% treatment efficiency (Gong et al., 2019). Removal efficiencies of metals calculated as concentrations (65.4%–95.7%) were lower than removal efficiencies calculated as loads (85.4%–99.4%). High pollutant loadings did not impact photosynthesis rates or chlorophyll content for most plants, though the height of shrubs was significantly affected. A laboratory-scale biofiltration unit was built and operated in Malaysia to examine the performance under tropical rainfall conditions (Hermawan et al., 2019). The system was split into two hydraulically isolated sections, each section planted with a native plant species—*Cyperus alternifolius* or *Pedilanthus tithymaloides*. Media comprised of washed sand graded to meet a target infiltration of 200 mm/hr, and the system was dosed with a synthetic stormwater blend comprising of TP, TN, and six heavy metals. The deeper-rooted *C. alternifolius* had better infiltration rates, while both sections performed equally well (67.3% and 62.5%) in removing TP. The study also showed that the top 100 cm of the system was where most of the TP and heavy metals accumulated, and therefore, it was the most active treatment layer in the system. Heavy metal removal exceeded 90% for most metals (Cu, Mn, Ni, Pb, and Zn) except Fe (76%).

Field, laboratory, and modeling performance studies: *modeling studies*

A modeling tool developed by Baek et al. (2019) combined the World Wide Hydrology Model version 4 (WWHM4) and the Hydrological Simulation Program—Fortran (HSPF) to determine optimal LID placement at the watershed scale. The model, called the Korea—Low Impact Development Model (K-LIDM), demonstrated through a sensitivity analysis the importance of the saturated hydraulic conductivity (Ksat) in the overall hydraulic performance of a network of bioretention systems. Other critical parameters were the size of the system and texture of parent soils. Another modeling approach to optimize bioretention design parameters was conducted using the RECHARGE model, where the model was validated against field measurements taken from a bioretention system in Singapore (Wang, Chua, & Shanahan, 2019). The authors showed that detention depth, the ratio of catchment to bioretention areas, and saturated hydraulic conductivity were most critical to hydraulic performance of bioretention systems. The SWMM-LID model in conjunction with SWMM's groundwater model was used to simulate the influence of a fluctuating groundwater table on runoff from a single bioretention cell (Kim et al., 2019). Model performance was evaluated by comparing observed storm flow volumes with predicted volumes. Inclusion of the groundwater component improved model performance, R^2 values increased from 0.69 to 0.95, and the percent difference between observed and predicted values decreased from 18.22% to 3.49%.

The abilities of the SWMM model to predict water quality outflows from a bioretention system were tested by Gülbaz (2019). The model's flow predictions were calibrated with data observed from a large (40 m^2) laboratory-scale impervious surface hydraulically connected to a large (0.23 m^2) bioretention column. The study showed that the model did not predict water quality concentrations in the bioretention outflow well; however, pollutant concentration predictions emanating from the impervious area (bioretention influent) were well predicted. SWMM was also used to assess the impact of rainfall conditions and rain garden proportion on stormwater retention and water quality in Xi'an, China (Li, Ma, Ma, Li, & Zhang, 2019), and the impact of LID (vegetated swales and rain gardens) in Kuala Lumpur, Malaysia (Rezaei et al., 2019). Li et al. (2019) found that rainfall intensity was the primary influencing factor for water quantity concerns while the rain garden proportion impacted water quality. Rezaei et al. (2019) also saw a positive impact on water quality from the implementation of LID. The model was most sensitive to the percent imperviousness as it significantly impacted runoff and peak flow. The model performed appropriately for event up to 70 mm of rainfall and a return period of up to 10 years (Rezaei et al., 2019). Evapotranspiration (ET) by bioretention systems was modeled by Hess, Wadzuk, and Welker (2019) using both Hargreaves and ASCE Penman–Monteith models for calculating ET. The models were modified using observed ET data measured from three weighing lysimeters planted with black chokeberry, seaside goldenrod, and switch grass. The lysimeters had varying compositions of sand silt and clay content, two with freely draining outlets, and one with an IWSZ. The modified models performed better than the unmodified at the daily scale. The authors suggest that if an unmodified version of either model is to be used, then the models should only be used for storm-scale events. They also conclude that the unmodified Hargreaves model is better than the unmodified ASCE Penman–Monteith at predicting ET for systems with a sand IWSZ, on a per-storm basis.

Climate change implications to bioretention performance were evaluated by three studies. A modeling approach using a continuous simulation hydrologic model (RECARGA) driven by baseline and climate projection scenarios to calculate the cumulative risk of system overflows was developed by Lewellyn and Wadzuk (2019a). For a bioretention system in the Philadelphia area, every climate scenario modeled posed a greater cumulative annual risk, particularly affecting those systems with high ponding and low infiltration rates. The use of underdrains and real-time outlet control were suggested as possible climate adaptation strategies. In a follow-up study, bioretention systems with increased design ponding depths were shown to lower the overall cumulative risk of system failure by overflow (Lewellyn & Wadzuk, 2019b). Systems built in native soils with high hydraulic conductivity were also associated with lower risk. Bioretention performance under predicted climate change scenarios for Guangzhou, China, was tested within a modeling framework using the SWMM by Wang et al. (2019). The work showed that based on the bioretention design parameters used for the modeling exercise, the systems could only handle high-frequency short-duration storms under predicted climate change conditions, failing to manage runoff from low-frequency long-duration storms.

The evaluation of environmental and economic implications of various bioretention design configurations was made using a life cycle cost analysis (LCCA) and a life cycle assessment (LCA) framework. Three design configurations were tested, using three depths of IWSZ (30, 45, and 60 cm) and three plant palettes (grouped by ability to uptake TN). All the design configurations comprised a mulch, soil, and sand media, with an underdrain. The analysis showed that designs with greater IWSZ depths and plants with high TN uptake improved overall TN removal, but these increases were partially offset by higher maintenance costs associated with plants and deep IWSZ. The authors concluded that an IWSZ is better than just plants for TN removal, both from an LCA and LCCA perspective (Xu & Zhang, 2019).

Enhanced media

A statistical analysis of treatment flow rates using 22 mixes of commonly used bioretention media mixes from across the United States was tested by Sileshi, Pitt, and Clark (2019). The median particle size, uniformity coefficient, and organic matter content were the most influential factors controlling treatment flow rates. Greater sand content in the media with more uniformly sized particles was associated with higher flow rates. When media with greater organic matter content was compacted, flow rates were significantly decreased. The adsorption of dissolved metals in stormwater by ten commonly used filter materials was tested by Søberg, Winston, Viklander, and Blecken (2019) by adopting a laboratory batch and kinetic adsorption methodology with both single- and multimetal solutions. Filter materials comprised mixtures in various combinations of the following materials: sand, biochar, compost, pumice stone, chalk, clay, and silt. No one filter material performed best across all metals; however, filter materials with high pH, low organic material, large specific surface area, and uniformly sized particles performed the best. The removal of orthophosphate by bioretention columns filled with a sandy loam media and a water treatment residual amendment (15% by weight) was demonstrated by Qiu, Zhao, Zhao, Wang, and Fu (2019). They reported removal rates exceeding 99% with 10 synthetic storm events applied over a 50-day period. They also showed that NH_4-N removal was consistently over 94%. NO_3-N and TN removal was improved with the presence of an IWSZ, NO_3-N removal increased from 21% to 85%, and TN removal increased from 32% to 75%.

Iron filings as an additive to bioretention media were shown to improve the removal of N and P in a bioretention column study (Chang, Wen, & Wanielista, 2019). Combinations of sand with a 3.8% and a 5% content iron filing mix (v/v) were compared with a natural soil control. The media containing 5% iron filings also included tire crumb and pure clay and was associated with higher N and P removals. The enhancement of denitrifying processes by wood chips in an IWSZ was examined by Igielski, Kjellerup, and Davis (2019) using two laboratory-scale columns, one with a free-draining outlet and the other with an IWSZ created with an upturned elbow. The work demonstrated that the wood chip substrate and the 2.6-day hydraulic retention time reduced TN concentrations from 3.0 mg/L to less than 0.01 mg/L. Nitrogen removal using wood biochar (18% w/w) in the unsaturated zone and zero-valent iron (10% w/w) in the saturated zone was tested in a laboratory setting using a synthetic stormwater blend (Tian et al., 2019). Removal of NO_3-N was greatest in the column with biochar and the zero-valent iron. The study showed that most removal of NO_3-N occurred in the unsaturated zone, attributable to treatment by biochar.

The removal of nutrients and PAHs from stormwater collected from a roadway was examined by Jay, Tyler-Plog, Brown, and Grothkopp (2019). They carried out the study using laboratory columns containing four replicates of 13 media types and a sand-only control. Media types ranged from high-Fe biosolids and biosolids mixed with yard and food compost stocks. Additives to the mixes included oyster shells, water treatment residuals, soil, and sawdust. Results showed that nutrients in the effluents were positively correlated to the amount of compost used in the media. Metal (Cu and Zn) removals also decreased as compost content increased between 20% and 80% (v/v). PAH removal was higher using biosolids–yard waste compost compared with food–yard waste compost. No single mix performed consistently well or poorly across the suite of analytes tested.

Nutrient removal by combinations of a bioretention soil mix (BSM) and several additives or modifiers was tested by Jiang, Li, Li, and Li (2019a). The BSM comprised a mix of river sand, soil, and wood chips (65:30:5 b w/w). Ten modifiers were added to the BSM and tested for ammonia and soluble reactive phosphorous (SRP) removal through isothermal adsorption batch testing followed by laboratory-scale minicolumn tests to analyze water holding, infiltration, and cost elements. The study incorporated analytic hierarchy process to meld all the elements (infiltration, water holding, adsorption, lifespan, and cost) to create a ranking of BSM + modifier combinations: For SRP removal, BSM + 10% green zeolite was most effective; for ammonia, BSM + 10% fly ash performed the best. In a follow-up study, Jiang, Li, Li, and Li (2019b) using the same BSM and modifiers showed that for COD, TP, and TN removal, BSM + 10% WTR, BSM + 10% green zeolite, and BSM + 10% fly ash were better than just BSM, respectively. They also showed that load reduction rates decreased with larger storm volumes but increased with influent pollutant concentrations.

Microbial diversity and microbial metabolic processes in bioretention media enhanced with fly ash were evaluated through a series of column studies (Zuo, Guo, Wu, and Yu (2019). Some columns included media in layers, while others incorporated homogeneously mixed media. Columns also included saturated zones with different saturation depths. Eleven dominant microflora were observed in the media. The removal of NH_4-N decreased with increased depths of the IWSZ, while NO_3-N removal increased with IWSZ depth. Correspondingly, along the IWSZ depth gradient, ammonia-oxidizing bacteria decreased in abundance as IWSZ depths increased from 20 cm to 60 cm, while nitrogen-oxidizing bacteria increased along that same gradient. TP removal was shown to have no measurable relationships with the measured microbial community. Bottom ash from a refuse incineration incorporated into a standard bioretention mix of soil, sand, and gravel performed well in the removal of TN, TKN, and TP (You et al., 2019). The mixes were housed in columns with an IWSZ. Removals for a simulated 2-year storm were 58%, 66%, and 97% for TN, TKN, and TP, respectively. For a larger event with twice the concentration of nutrients in the inflow, removals were 70%, 82%, and 82%, for TN, TKN, and TP, respectively. The role of spent lime as an amendment to bioretention soil media was tested by Shrestha et al. (2019) in a two-part study comprising field and laboratory components. Phosphate concentration effluent from media without spent lime was shown to be 50% more than media with spent lime, for both field and laboratory testing.

The removal of *E. coli* from stormwater with metal-amended water treatment residuals (WTR) was tested using a batch adsorption isotherm methodology (Xu et al., 2019). The WTR were modified with Fe_2O_3, CuO, Pt, and Ag treatments. The metal-modified WTRs adsorbed more *E. coli* than the unmodified WTRs, with the CuO-modified WTR adsorbing the most. Inactivation of bacteria by CuO was also shown, suggesting that CuO-modified WTR can increase both adsorption and inactivation of *E. coli* in stormwater. The removal of fecal indicator bacteria by large sand biofilters augmented with biochar was tested by Kranner, Afrooz, Fitzgerald, and Boehm (2019). The effect of including a saturated zone was also tested. The experiment comprised four treatments, each replicated three times, with a sand-only system with and without a saturated zone serving as controls. The systems were conditioned over a 61-week period with natural stormwater and then dosed at the end with a stormwater spiked with 1% (by volume) raw wastewater. *E. coli* removal was consistently observed within all the systems during the conditioning phase, biofilters with biochar outperforming others for the first 30 weeks, after which all the systems performed with uniformity. After the conditioning phase, biochar-amended systems once again outperformed the sand-only systems when tested with stormwater spiked with wastewater. The rebound in performance is hypothesized to be related to the differences in influent stormwater chemistry (pH, ionic strength, and normal organic matter abundance) and phenotypic difference in transport of *E. coli* associated with stormwater and those associated with wastewater, due to physiochemical association with particulates. Biochar derived from fluvial deposits (6% w/w) mixed with garden soil was compared with an activated carbon (6% w/w) garden soil mix to examine nutrient removal when a synthetic stormwater mix was passed through bioretention test columns (Sang, Huang, Zhang, Che, & Sun, 2019). The removal of nitrogen (34 ± 20%,) was greater with the biochar-amended mix, while the activated carbon performed better at phosphorous removal (95% ± 3%). Five experimental media comprising a sand–soil mix with amendments and saturated zone were tested in a laboratory column study using a synthetic stormwater blend. Amendments used for this study included rice husk biochar and iron-coated biochar. The iron-coated biochar columns performed best for COD, NH_4-N, and TP removal. Columns with the biochar amendments performed better than columns without biochar in terms of NH_4-N removal (Xiong et al., 2019).

Vegetation, trees, and other biota

The importance of the rhizosphere in increasing microbial abundance was demonstrated by Chen, Liu, et al. (2019) who showed that bioretention columns with plants had an increased abundance of 16S rRNA, nitrifying, and denitrifying genes in the soil, compared to the no-plant group. In a study on plant traits that best predicted the removal of nitrate and phosphate removal in bioretention columns, Chen, Huang, et al. (2019) observed that dry plant biomass was somewhat correlated to nitrate and phosphate removal, with planted native tree biomass most correlated to nitrate removal. Nitrate removal was also closely related to the leaf dry biomass of fast-growing plants, while phosphate removal was correlated to the root biomass of slow-growing plants.

A study of tree pits as bioretention systems was conducted using data collected from 24 tree pits in two locations within the city of Montreal, Canada (Frosi, Kargar, Jutras, Prasher, & Clark, 2019). The experiment employed a split–split-plot design with soil organic matter (SOM), sidewalk permeability, and lawn presence as varying factors. Soil solution samples were collected from three depths in the soil pit using preinstalled lysimeters. Results from the study suggested that street tree pits are an effective means to reduce contaminant (Na, Ni, Cu, Zn, and DOC) flux and that pits with higher SOM were correlated with greater removal of Na and Cu. The role of trees in managing influent stormwater volume when planted in bioretention systems was tested by Tirpak, Hathaway, and Franklin (2019). They showed that mesocosms planted with four tree saplings had greater losses of water through evapotranspiration when compared to unplanted mesocosms. Evapotranspiration accounted for between 8.2% and 37.5% of daily water loss, with mesocosms planted with red maple losing the most (3.2 mm/day). A study of 21 established urban forest patches (tree canopy of 0.1 ha with shrubs, trees, and woody debris) in Baltimore, Maryland, USA, determined 68% of the historical rainfall could be infiltrated by the urban forest soils. The infiltration capacity was found to be temporally dynamic and based on soil moisture conditions (Phillips, Baker, Lautar, Yesilonis, & Pavao-Zuckerman, 2019).

Reviews

A review of ten modeling and field studies on the performance of vegetated grass filters and grass swales next to roadways by Gavrić, Leonhardt, Marsalek, and Viklander (2019) showed that most studies emphasized the removal of TSS associated with road runoff. The authors also point out that besides settling of particulates, other remediation processes such as plant uptake, microbial degradation, and adsorption/desorption processes are not systematically characterized. From the modeling studies reviewed, limitations identified include the lack of nonuniform pollutant loading rates, submerged flow conditions, and lateral inflows to swales—all conditions that are typical of real-world conditions. The characteristics of bioretention performance outlined in multiple studies were reviewed by Goh et al. (2019) for their relevance to nutrient removal in tropical climates. Based on these reviews, the authors propose that both mulch and submerged zones could be removed from tropical bioretention design specifications. The authors argue that these two design elements are based on data collected from high-latitude study sites where prolonged dry periods necessitate these elements but are not needed in high rainfall conditions as experienced in the tropics.

A synthesis of data from 79 bioretention performance studies was conducted by Wang, Zhang, and Li (2019). Using several statistical techniques, they showed that pollutant removal was significantly related to bioretention surface area, media depth, and the presence of saturated zone, soil, and vegetation cover. Removal of TSS was best achieved with unplanted sand-only systems, while total nitrogen removal was highest when media depth exceeded 58 cm and contained some organic material. Organic material in the media and the presence of vegetation were optimal for TP removal. Generally, grasses in bioretention and mixed types of vegetation outperformed systems planted only with trees and shrubs in terms of pollutant removal. The authors propose a critical need to report bioretention performance in consistent terms to help similar future synthesis efforts.

Common themes and future work

Compared to 2018, there were considerably more column studies reported on in 2019 with 21 studies using laboratory-based columns, four employed batch kinetics and isotherm methodologies, and one study used a large mesocosm to simulate bioretention performance. Three studies focused on bioretention performance in tropical and subtropical climates. A review of the current body of knowledge associated with bioretention practices and how these practices may effectively contribute to fit-for-purpose urban water sources was conducted by Payne, McCarthy, Deletic, and Zhang (2019). They call for improved understanding of trace pollutant and pathogens, improved protocols for validation monitoring, cheaper but reliable measurement capabilities of surrogates of continuous performance, real-time control strategies, and lastly a better understanding of the relationship between maintenance and water quality.

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 38 papers were published in 2019 to describe one or more of these functional characteristics of permeable pavement systems. This body of work includes a review of pervious concrete (PC) as a substitute material for pedestrian pavements in dense urban cores (Moretti, Di Mascio, & Fusco, 2019). For areas that comprise over 80% of impervious surface, a replacement of just 6% of the area with permeable pavements can make considerable differences to the urban heat island effect, improve architectural and aesthetic value, and reduce surface runoff and inputs to the stormwater system. However, the importance of maintenance was emphasized.

Hydraulics and related properties

A study examining hydrologic alterations of stormwater by three types of permeable pavements showed that peak flows were lowered between 31% and 100% across all three types of pavements. PC pavements were best at eliminating surface runoff compared to interlocking block pavement with gravel, and PICP (Alam, Mahmoud, Jones, Bezares-Cruz, & Guerrero, 2019a). The porosity of PC pavements ranging from 20% to 30% was shown to have no effect on the fatigue life of pavement sections subjected to repeated wheel loads (AlShareedah, Nassiri, & Dolan, 2019). The influence of aggregate gradation and compaction in the base layer of a permeable pavement in terms of base-layer permeability and static water level was tested by Koohmishi (2019). Rounded gravel expectedly had a lowered compaction and greater permeability than angular gravel. However, the particle size distribution of the aggregate was shown to have a greater influence on permeability and static water level than compaction or aggregate morphology.

A comparison of three common field infiltration test protocols for PC was made by Zhao et al. (2019) and validated against direct laboratory measurements. The constant-head single-ring infiltration (CH-SRI), falling-head single-ring infiltration (FH-SRI), and the double-ring infiltration (DRI) tests were evaluated. The DRI method with inner ring >200 mm and the outer ring >500 mm was the most accurate compared to laboratory controls. The CH-SRI and FH-SRI tests tended to overestimate infiltration rates because of the inability to restrict lateral flow in the pavement. The work also outlines a new field double-ring infiltrometer setup to deal with the typical challenges associated with conducting the DRI test. A full-scale infiltration testing (FSIT) method was developed by Boogaard and Lucke (2019) to accurately characterize infiltration rates for permeable pavement installations. The FSIT essentially involves flooding a large pavement area with a large volume of water, using temporary sand-filled barriers to hold the water over the pavement surface at depths of 50 mm to 90 mm. The experiments were carried out at 16 permeable pavement sites in the Netherlands. The authors state that this method is more realistic of true field conditions compared to the standard single- and double-ring infiltrometer tests that are typically employed. An argument to use hydraulic conductivity as a measure of permeable pavement performance in place of the typically used surface infiltration metric was put forward by Chu and Fwa (2019). The authors posit that hydraulic conductivity being based on Darcy's law for laminar flow, and the modified Darcy's equation for turbulent flow, had a more sound theoretical basis compared to the infiltration rate measure which is dependent upon the hydraulic gradient imposed on the pavement. The NCAT permeameter or the k-Tester was proposed as possible instruments to measure hydraulic conductivity of permeable pavements.

The performance of porous asphalt (PA) and permeable interlocking concrete bricks (PICB) was evaluated in terms of hydraulics and thermal properties (Cheng, Lo, Ho, Lin, & Yu, 2019). Runoff peak flow reductions varied from 16% to 55% for large high-intensity storms and smaller long-duration storms, respectively. Lowering of infiltration rates due to clogging was greater for PA (70%–80%) compared to PICB (25%–50%) over the 15-month study. The temperature of PA and PICB pavements increased faster with rising air temperatures compared with standard pavements and similarly lost heat quicker as air temperatures dropped. The authors suggest that PA and PICB pavements are therefore better than standard pavements in mitigating the urban heat island effect. Temperature sensor trees embedded in PC pavements at three locations in the vertical profile enabled Nantasai and Nassiri (2019) to evaluate the thermal properties of these systems. The study showed that temperatures of the pavement surface fell below freezing point for a total of 24 days over a single winter season, while at a depth of 5.5 inches, below-freezing temperatures were measured for only 12.5 days. To help schedule pavement winter maintenance around near-frost conditions, a predictive linear regression model that incorporates meteorological indices to model surface pavement temperatures was developed.

The effects of rainfall intensity and topographic slope on infiltration rates of permeable pavement were examined using a physical experimental platform that allowed for the control of longitudinal and cross-slopes of pavements, as well as rainfall intensity (Hou et al., 2019). Permeable pavements were modeled with acrylic plates punched with holes of varying sizes to replicate low, medium, and high infiltration pavements. Plates were subjected to artificial rainfall events, and water that ran off the surface of the pavements, or infiltrated through, was captured and measured. The relationship between infiltration rates and slope was best described by a power function, where an increase in slope varied inversely with infiltration rates. Cross-slope had a greater impact on infiltration rates compared to longitudinal slope. The transport of sediments in PICP under varying rainfall intensity conditions was examined using an innovative experimental platform which enabled tracking of sediment transported through the paver pores and across the surface of the paver to the paver edge (Yang, Beecham, Liu, & Pezzaniti, 2019). Sediments transported to the paver edge were assumed to be those that end up in the space between pavers in a field setting. Higher intensity of rainfall corresponded to a greater likelihood of sediments being flushed through the paver pores. Between 33% and 46% of sediments were transported to the edge of paver, around 50% ended up being trapped within the paver pores, and less than 1% passed through the paver pores to the other side.

The effect of tree roots growing below permeable and impermeable pavements showed that over a 5-year period, the gravel layer below the permeable pavement deterred root growth immediately below the pavement (Johnson, Moore, Moore, Cameron, & Brien, 2019). Shallow root growth was both smaller in diameter and observed at deeper positions below the permeable pavement, compared with the impermeable pavement. The authors carried out the study in Adelaide, Australia, and concluded that properly built permeable pavements will mitigate pavement damage and maintenance brought on by the growth of tree roots. An almost identical study by Lucke and Beecham (2019) conducted in Brisbane, Australia, over a 4.5-year period corroborated the idea that the gravel layer below permeable pavements forces tree roots to grow deeper into the soils below to seek water and nutrition. The forcing of tree roots to deeper strata functionally protected the pavements from tree root damage. The control standard pavements without a subsurface aggregate layer were severely damaged. A 100-mm deep gravel layer resulted in minor pavement damage, while a 300-mm layer showed no damage at all.

Modeling

The WinSLAMM model was used to assess the hydrologic performance of three types of permeable pavements over a wide range of rainfall events (Alam, Mahmoud, Jones, Bezares-Cruz, & Guerrero, 2019b). The study showed that the calibrated model's runoff predictions can have a 30% error. The study also showed that compared with PICP, and interlocking block pavements with gravel, PC pavements are best at managing stormwater runoff. Using PC enabled a footprint that was 50%–60% smaller, compared to the other two pavements, while receiving the same water management benefits. The hydraulic performance of PICP pavements at five sites was observed by Vaillancourt, Duchesne, and Pelletier (2019) over a 12-month period. Observed data were then used to parameterize the infiltration capacity of permeable pavements in PCSWMM. The parameterized model was applied to four real urban watersheds by replacing all pervious pavements with impermeable pavements, two with combined sewer systems and two with separated systems. Over a simulated 8-year period, model results showed a 65% reduction in flow volumes in combined sewer systems and 30% in the two separated systems. Surface flooding of all four watersheds was reduced between 24% and 81%.

A three-dimensional groundwater–surface water model was calibrated based on observed groundwater levels at a green stormwater infrastructure site comprising tree trenches next to a PC sidewalk in Maryland (Barnes & Welty, 2019). The study showed that summer rainfall captured by the pavement contributed to groundwater recharge despite evapotranspiration demand exceeding precipitation. When winter melt was also included, infiltration from the site was shown to contribute to groundwater recharge over the entire year. A physically based hydraulic model (FlexPDE) using a fully integrated partial differential equation solver was calibrated and validated to describe the hydraulic properties of permeable pavements (Cortier, Boutouil, & Maquaire, 2019). The model was shown to have good reliability (NSE values of 0.969 and 0.891). The model also suggested that the saturated hydraulic conductivity of parent soils below the pavement is the most critical parameter in the hydraulic performance of the pavement. A framework for risk-based analysis of permeable pavement performance was developed by Kalore, Babu, and Mallick (2019). They based the framework on a capacity–demand model, with demand modeled as the required design permeability of the pavement and capacity based on the actual layer permeability as constructed in the field. The authors showed that the ideal combination of safety and economy required an optimum combination of pavement thickness and base-layer gradation.

Water quality

The contributions of the surface wearing layer and the lower aggregate storage layer toward the removal of stormwater pollutants from infiltrating stormwater were quantified by Liu et al. (2019). The study showed that most pollutants (TSS, NH_4-N, NO_x-N, TP, and COD) were removed in the upper wearing layer, which in this study comprised permeable ceramic brick. A thicker aggregate storage layer comprising of a smaller gravel gradation further improved removals of most pollutants (TSS, TP, NH_4-N, Cu, and Cd). A numerical model to predict total pollutant removal of a permeable pavement system in terms of individual removals of the wearing surface and the lower aggregate gravel layer was developed. The model effectively predicted TSS, TP, and NH_4-N removals within ±7% of observed pollutant-specific removals.

The hydraulic and water quality performance of PC under two rainfall regimes (Atlantic and Mediterranean) were tested by Hernandez-Crespo, Fernandez-Gonzalvo, Martin, and Andres-Domenech (2019). Between 16% and 62% of the rainfall applied to the pavement infiltrated to the storage layers below. Leaching of nutrients from street dirt applied to the surface of the pavements showed that 25% of the mass of N applied to pavement surface was measured in the leachate, with concentrations of N and P increasing with higher intensity rainfall events.

A study on pollutant removal from stormwater infiltrating through a PC system demonstrated statistically significant removals of TSS, NO_2-N, COD, and PAHs (Pilon, Tyner, Yoder, & Buchanan, 2019). Sulfate and pH concentrations increased significantly between influent and effluent sampling locations. The reduction of TSS was greatest (80%) by PC compared with other pavements tested. Other pavements tested comprised PICB, and interlocking block pavements with gravel (Alam et al., 2019a). BOD5 removal with interlocking block pavements with gravel was greatest (46%) when compared with other pavements. Another study that examined removals of stormwater pollutants by three types of permeable pavements showed a significant reduction in sediment and sediment-bound pollutants over a 22-month period (Selbig, Buer, & Danz, 2019). All three pavements removed 60% of TSS, while PICP and PA pavements showed a 20% reduction in TP, and an PA removed 43% of TP. The highest metal removals occurred with PC (49%) and the lowest with PA (40%). The median pH in effluent from PC was 10.2 compared to 7.5 and 7.8 for PICP and PA, respectively. The high pH of effluent from PC was hypothesized to be responsible for the better metal and TP removals by PC.

The removal of several pollutants associated with stormwater runoff was tested in a replicated field study by Jayakaran, Knappenberger, Stark, and Hinman (2019) at the Washington Stormwater Center. The study conducted over a 5-year period showed that PA pavements are particularly well suited to the removal of particulate and particulate-associated pollutants. Coarse sediments (98.7%), total Pb (98.4%), total Zn (97.8%), and total suspended solids (93.4%) were all removed at significant rates, while dissolved constituents and PAHs were not. The work showed that PA can meet primary (TSS) and phosphorous (TP) treatment performance goals for stormwater practices as stipulated by the Washington State Department of Ecology.

Water quality samples obtained over an 8-year period from influent and effluent positions enabled the characterization of the long-term pollutant removal rates of PA, PC, and permeable interlocking concrete pavers (PICP) (Razzaghmanesh & Borst, 2019). Results from this work showed that PC and PICP performed similarly over the 8-year period across all pollutants examined (NH_3, NO_2, NO_3, PO_4, TN, and TOC). PA performed worse than PC and PICP in terms of NH_3 and NO_2 removal, with removal rates of all N species also decreasing over time for all three types of pavement. PA did a better job with PO_4 removal compared to the other two pavement types, but over time, PO_4 removals also decreased. PC was the only pavement type that showed improved PO_4 removals over time.

Innovations

Infiltration testing of an innovative load-bearing permeable pavement with a unique structure and design called the JW Eco-technology pavement was conducted by Chen, Chen, Chen, Chen, Lecher, and Davidson (2019). The pavement reportedly has the load-bearing capacity of a standard roadway. JW Eco-technology pavement comprises a plastic grid structure placed over a lower gravel aggregate storage layer. Standard concrete is poured into the plastic grid framework until it is level with the top of the grid. The plastic grid incorporates narrow aperture standpipes that act as weep holes, allowing water from the impervious concrete surface to drain into the storage layer below. Infiltration testing of JW Eco-technology pavement was shown to be comparable with a standard PC pavement, based on both static and falling-head infiltrometer tests.

The use of alternative binders to improve the strength of PA pavements was tested by Cai et al. (2019) using three waste-based high-viscosity asphalt binders that contained blends of crumb rubber powder and recycled oil. The study showed that these waste-based binders match the performance of standard materials in terms of chemical stability and viscosity, at both high and low temperatures. Using a laboratory-based experimental framework, Hu, Dai, and Pan (2019) found that adding activated carbon to PA mixes increased the PA content due to high absorptivity and specific surface area of activated carbon. While bonding between the asphalt and aggregate increased in the presence of the activated carbon, the mix tended to be softer with the higher PA content. A PA layer that was 6 cm thick with an air void content of 18% was recommended. A photocatalytic layer of Fe_2O_3 nanoparticles (NP) when incorporated into permeable concrete at 3% and 5% of cement weight was found to have no effect on the removals of several microbiological (*E. coli*, *Pseudomonas aeruginosa*, *Aeromonas hydrophila*, and *Enterococcus faecalis*) and physicochemical pollutants ($N - NH_4^+$, $N - NO_3^-$, phenol, PO_4^{3-}, Fe, Mn, and Pb) when compared to controls without NP (Ortega-Villar et al., 2019). However, all the permeable concrete samples, including the controls, removed all pollutants at a significant level. The only exceptions were *Enterococcus faecalis*, $N - NH_4^+$, and phenol.

The use of recycled waste glass cullet and recycled concrete aggregate to improve the performance of PC was tested by Lu, Yan, He, and Poon (2019). Despite a loss of compressive strength, the permeability of PC was shown to increase with additions of these components. An aggregate mix comprising 50% glass as fine aggregate and 50% recycled concrete as coarse aggregate developed enough strength and permeability for use as pedestrian pavers. Bottom ash from municipal solid waste incinerators was used as a substitute for natural aggregate material in PA pavements by Zhao and Zhu (2019). They sought to evaluate the potential for heavy metals to leach out of the fly ash as water infiltrated through the pavement matrix. The study illustrated that particle sizes of fly ash and contact time were critical determinants of heavy metal concentrations in the leachate. Smaller fly ash particles and longer contact times were associated with higher heavy metal concentrations.

A phenolic foam layer called OASIS® was tested for its ability to improve hydraulic performance of the pavement by increasing the amount of runoff that can be retained within the pavement structure (Heweidak & Amin, 2019). The study showed that a 35-mm OASIS® layer attenuated peak flows more than the systems without OASIS®, delaying peak flows by 97% for a 100 mm/hr event to 27% for a 563 mm/hr event. A base layer comprising expanded shale aggregate, aluminum-based water treatment residuals, and a psyllium-based binder below a laboratory-based permeable pavement experimental setup was shown to remove dissolved phosphorous, total Cu, and total Zn. In the presence of an IWSZ with a carbon source, a 33% reduction in total nitrogen load was also observed (Ostrom & Davis, 2019). Kuruppu, Rahman, and Sathasivan (2019) also showed that nitrogen removal was highly effective when an IWSZ with a carbon source was used. PC pavement with these two features was found to perform twice as well in terms of total inorganic nitrogen when compared to a control PC system without these two features. Including an IWSZ and a carbon source also prolonged nitrogen removal over the course of a storm, with removals consistently occurring even at later stages of the storm event, a phenomenon not seen in the control PC.

Changes in electrical resistivity were used as a proxy for changes in porosity due to clogging of a PC sample (Cui et al., 2019). An electric field was created between the upper and lower surfaces of the pavement sample by circulating a 10% salt solution through the pavement core and applying an alternating current power of 12 V. The experiment showed that pore clogging comprised three phases: quick clogging, temporary mitigation of clogging, and slower progressive clogging. Computer tomography (CT) scanning was used to evaluate the equivalent diameter of pores and the relationship between pore clogging and particle size distribution of the clogging material

(Zhou et al., 2019). The work showed that pore size was related primarily to aggregate size and secondarily to cement–aggregate ratios. The degree of clogging in PC was related to the ratio between size of clogging particle and size of pore, with ratios between 0.6 and 0.8 yielding clogging. Clogging of PA pavement cores was modeled in a laboratory setting by subjecting several cores with porosities ranging from 13.6% to 31.8% to water and sediment loads (Garcia, Aboufoul, Asamoah, & Jing, 2019). The researchers also created artificial transparent resin cores with porosities identical to the asphalt samples, subjecting those cores to the same water and sediment loading regime. The transparent resin cores were created through a process that involved computerized tomography scanning and three-dimensional printing. The transparent cores enabled the imaging of pore clogging processes. The study showed that among the parameters of tortuosity, average pore diameter, macroporosity, and Euler number, pore size was the most critical factor in determining clogging. Smaller pores clogged faster, with most of the clogging occurring within 10 mm of the pavement surface.

Common themes and future work

Several studies in 2019 focused on elucidating clogging of permeable pavements using innovative methods to measure and visualize clogging rates. Two studies specifically looked at how gravel aggregate layers below permeable pavements dissuade tree root growth, showing that permeable pavements are likely to be more immune to tree root damage compared to their impervious counterparts. Incorporations of IWSZ with a carbon source showed promise in terms of nitrogen removal, a design innovation from the realm of bioretention.

A review of past studies conducted by Kuruppu, Rahman, and Rahman (2019) concluded with the following as possible future research needs in the realm of permeable pavement performance: (a) improved modeling of design variables with structural, hydraulic, and environmental performance; (b) developing standard maintenance protocols to restore infiltration rates; and (c) improved capacity of permeable pavements to support higher vehicular loads and speeds. In another review of major research related to permeable pavements by Weiss, Kayhanian, Gulliver, and Khazanovich (2019), five areas of future work identified were as follows: (a) methodologies to measure subgrade infiltration rates; (b) data gaps related to fuel consumption, noise reduction, human comfort, and climate change; (c) processes that drive contaminant reduction within pavements; (d) long-term (<20 years) performance of pavements; and (e) improved maintenance practices and frequencies.

Green roofs

In 2019, there were at least 36 articles published which focused on the study of green roofs. Green roofs are an attractive rooftop stormwater management approach primarily used in highly developed urbanized areas with minimal greenspace. There are many benefits of green roofs. This subsection focuses on those that explicitly apply to stormwater management, including the role of structural features and vegetation on green roof hydrologic performance, the impact of green roofs and potential substrate amendments on runoff water quality, and the overall modeling and cost–benefit of green roof installations.

Field, laboratory, and modeling hydrologic performance studies

The retention and detention capabilities of green roofs have become well established over the years. For example, from 2009 to 2014, mean retention rates of two green roofs in Wroclaw, Poland, were 81.2% and 81.5% including full retention of 30%–35% of storms during the five-year study (Burszta-Adamiak, Stańczyk, & Łomotowski, 2019). These same roofs demonstrated detention that varied with storm depth including a delay in runoff of 1.5–1.7 hr for 5–10 mm rainstorms. Another full-scale study of green roof performance at the University of Calabria, Italy, noted a mean runoff volume of 32% for all rainfall events captured (Palermo, Turco, Turco, Principato, & Piro, 2019). The importance of the antecedent dry weather period in the runoff generation from a green roof between similar-sized rain events was highlighted. The van Genuchten–Mualem capillary pressure–saturation model was used to fit data prior to modeling with HYDRUS-1D.

The collection of full-scale performance data of green roofs has allowed for several research to explore modeling the long-term behavior of full-scale green roofs, many utilizing SWMM 5.1 (Hamouz & Muthanna, 2019; Johannessen, Hamouz, Gragne, & Muthanna, 2019; Liu & Chui, 2019). Liu and Chui (2019) utilized SWMM to compare the response of green roofs in Hong Kong, China, Beltsville MD, USA, and Sidney, NY, USA, to storms of increasing return periods. Although the values varied between locations, average runoff reduction increased with storm return period but plateaued at storms with longer return periods (i.e., 5–10 years). SWMM was also used to model green and gray roofs in Germany (Hamouz & Muthanna, 2019). The green roof model performed well under calibration, NSE of 0.94 and volume error of 3%, but deteriorated during the validation stage which utilized long-term continuous datasets. The model performance decayed further under winter conditions to an NSE of 0.56 and volume error of 30%. Long-term predictive capabilities of SWMM models were also an issue for Johannessen et al. (2019) where a similar range of volume errors was seen (between −4% and 28%) when building SWMM models for several similarly constructed green roofs in Norway. Laboratory parameters were compared to calibrated SWMM model parameters such as porosity, field capacity, and wilting point. Field and calibrated parameters did not necessarily match, but a combination of parameters was found which worked well for most of the green roofs in the study. Interestingly, all three SWMM studies presented hypothesized that errors in the model were in part due to errors in modeling evapotranspiration (ET).

The design of a green roof includes careful consideration and selection of many features including various membranes, storage and drainage layers, selection of the substrate and vegetation, and, if necessary, irrigation systems (Cascone, 2019). Of particular interest is the role of substrate in the hydrologic performance of a green roof. When compared to substrate depth, green roof slope, and vegetation type, the substrate material was found to be the greatest contributor to hydrologic performance of a green roof module (approximately 54%) likely due to the influence of porosity on the retention of the rainfall (Liu, Feng, Chen, Wei, & Deo, 2019). While all four of these parameters were found to be statistically significant, vegetation had the smallest impact on the green roof discharge. Liu et al. (2019) also found that the runoff from these test modules could be well predicted using the Taguchi method.

The choice of substrate material and design elements such as drainage mats will ultimately influence the holding capacity of the green roof design (Ladani, Park, Jang, & Shin, 2019). In an effort to replicate runoff behavior of green roof text modules, more detailed models can be used. For example, infiltration of the water into and migration through the substrate can be modeled with equations such as the Green-Ampt equation for infiltration and Darcy's law, an approach used in the Korea—Low Impact Development Model (K-LIDM) (Ladani et al., 2019). Also relevant is the choice of additional structures on the green roof such as the incorporation of photovoltaic panels. Green roofs with PV panels were found to have decreased retention compared to those without panels due to localized pooling where the water ran off the PV panel (Jahanfar, Drake, Sleep, & Margolis, 2019). This effect was greater for PV panels closer to the green roof surface translating into NRCS CNs of 93 for the green roof with no PV panels, 96 for PV panels 1.2 m from the green roof surface, and 97 for PV panels 0.5 m from the surface. It is important to note that PV panels are more efficient at cooler temperatures and therefore benefit from being closer to the green roof surface.

Green roof substrates tend to consist of a mixture of materials, and therefore, being able to predict the performance of a mixture of materials could allow for customization of substrate materials. Bollman et al. (2019) demonstrated that if the wet weight, water held, and long-term retention capabilities of individual materials are known, the performance of the mixture can be predicted while also acknowledging the long list of other substrate parameters impacting green roof function including thermal properties and nutrient/chemical capture for plants. The hydraulic conductivity of the mixture was more difficult to predict but is an important parameter in green roof performance. In a module-based experiment of low and high permeability substrate mixtures, the material with lower permeability and therefore greater potential retention capacity led to high variability in event-related retention (Skala, Dohnal, Votrubova, & Jelínková, 2019). This behavior could not be captured with a linear reservoir cascade model or nonlinear reservoir model. It was hypothesized that this was due to the lack of accounting for ET between rainfall events supporting the need to incorporate relevant ET processes in models.

Evapotranspiration (ET) has the potential to remove water from the system and improve retention performance. Under small storms, the role of plants of different water use strategies in the initial capture will be minimal if the substrate has the capacity to retain the storm. However, it is important to also consider the root system of the plants, particularly high water use strategy plants, which may create preferential flow paths in the substrate resulting in a counterintuitive decreased retention under big storms when compared to nonvegetated and low water use strategy plants (Zhang, Szota, Szota, Fletcher, Williams, & Farrell, 2019). Current ET models are mostly from agriculture applications and can struggle to capture the complex interactions between the vegetation, soil, and climate of a green roof. Ebrahimian, Wadzuk, and Traver (2019) found that the 1985 Hargreaves method was generally acceptable for continuous simulation of ET processes in green roofs. Based on the model, ET could be increased through the use of an undrained green roof system and/or finer soil, both of which would hold more water in the substrate.

The moisture of the substrate will influence ET and retention–runoff behavior of the green roof. In a module experiment, measured soil moisture dynamics demonstrated a simultaneous reaction to rainfall throughout the depth of the green roof instead of the predicted wetting front moving from the top down (Peng, Smith, & Stovin, 2019). Modeling of this behavior was most successful with Richard's equation which produced more conservative results when compared to the reservoir routing equation which often underestimated moisture (Peng et al., 2019). Richard's equation, coupled with the van Genuchten–Mualem capillary pressure–saturation model, was also used to explore the statistical importance of field capacity on peak flow rate attenuation of green roof modules. Prior to reaching field capacity, capillary storage was the primary mechanism controlling peak flow attenuation, but once the field capacity was reached, gravity storage and routing became the primary mechanisms for peak flow attenuation (Sims, Robinson, Smart, & O'Carroll, 2019). The attenuation and retention models were highly sensitive to the pore size distribution from the van Genuchten–Mualem model.

ET will decrease over time as water within the substrate is used up (Kaiser, Koehler, Schmidt, & Wolff, 2019). If extra retention can be incorporated into the design of the green roof, the stored water can be used to irrigate during drier periods optimizing ET rates. For thin substrates, short irrigation time periods will maximum ET values. In some climates, irrigation is already needed to support vegetation during prolonged droughts. The amount of irrigation is typically a fraction of the ET rates for the vegetation present but requires monitoring and calibration. Charalambous, Bruggeman, Eliades, and Camera (2019) irrigated two different plant species at 15% and 30% ET based on successful results from similar studies. However, under the 30% ET irrigation strategy only 20% of the *Frankenia laevis* and 88% of the *Euphorbia veneris* survived. Under 15% ET, 38% of the *E. verneris* survived, but during the experiment, it was determined none of the *F. laevis* would survive if irrigation was not increased.

The design of the green roof structure and choice of substrate and vegetation are influenced by the local economy and climate. For example, the predicted runoff reduction between six cities in Canada over a seven-year time frame varied between 17% and 47% based on location (Talebi, Bagg, Sleep, & O'Carroll, 2019). The economic climate will also influence the applicability and acceptance of green roof installations. A benefit–cost analysis in Jung-gu, Seoul, South Korea, compared five potential green roof projects, primarily focused on percent coverage of roofs. The study identified costs (structural safety inspection, construction, operation and maintenance, safety management and environment, and disposal) and benefits (carbon sequestration, reduction in cooling energy, stormwater management, air pollutant removal, social benefits of improved air quality, rooftop lifetime extension, urban aesthetics, and comfort) of green roof projects (Shin & Kim, 2019). The only scenario which produced a greater benefit than cost was implementation of green roofs on all rooftops. However, changes in construction costs or increases in perceived benefits, such as improved CO_2 sequestration based on optimized vegetation selection (Baraldi et al., 2019), could result in other acceptable scenarios. A similar analysis focused on the benefits, opportunities, costs, and risks of green roof installation in Malaysia (Tabatabaee, Mahdiyar, Durdyev, Mohandes, & Ismail, 2019). Exploitation of the benefits and opportunities while avoiding the costs and risks is the ideal scenario. According to experts consulted within the study, the most influential benefit, opportunity, cost, and risks are stormwater runoff mitigation capabilities, mitigation of the urban heat island effect, structural support, and irregular maintenance, respectively.

Water quality and substrate amendments

The question of whether a green roof acts as a source or sink of various water quality pollutants is an area of concern (Vijayaraghavan, Reddy, & Yun, 2019). Factors that may drive these results include rainfall, substrate composition, depth, and vegetation type. For example, Jeon, Hong, Jeon, Shin, and Kim (2019) identified initial reductions in heavy metals Cu and Zn and TSS, BOD, TOC, TN, and TP from green roofs compared to traditional roofs under small rainfall events. However, these same green roofs transitioned into a source of nutrients over 40 mm of rainfall. A second study comparing vegetated and unvegetated green roof modules determined the discharge from the vegetated modules had lower nutrients (NH_4-N, NO_3-N, and TN and TP) and TSS but greater chemical oxygen demand (COD) than the unvegetated green roofs (Gong et al., 2019). Higher TSS loads from unvegetated green roof modules were also detected in a study by Liu et al. (2019); however, the vegetated roofs had statistically higher TN than the unvegetated and showed greater loads of TSS, TP, and TN compared to traditional roofs. In addition, one of the substrate types tested showed statistically higher TN and TP, highlighting the role substrate can have in water quality. Given the common use of inorganic materials in green roof substrate and their low sorption capacity toward pollutants, Vijayaraghavan et al. (2019) recommended the use of additional organic materials, such as seaweed, crab shells, and biochar, as substrate amendments. The use of biochar as a substrate in 50 cm × 33 cm green roof test modules demonstrated a statistically significant improvement in pH buffering and discharge load reductions of TN and COD (Zhang & Wang, 2019). There was no statistically significant impact on water retention, or TP, TSS, and Fe loads in the green roof discharge.

Vegetation

As seen in the previous sections, there is much interest in the role of vegetation in the hydrologic function, and to a lesser extent water quality, of green roofs. Green roof vegetation can be impacted by factors such as shading (Aguiar, Robinson, & French, 2019), substrate heterogeneity (Vasl, Schindler, Kadas, & Blaustein, 2019), and temperature on and within the subsurface of the green roof (Baryła, Gnatowski, Karczmarczyk, & Szatyłowicz, 2019). The role of shading was found to be highly dependent on the species of vegetation. Artificial shade did not demonstrate a benefit when compared to the shade produced by the presence of another living plant (Aguiar et al., 2019). The shade was found to reduce the soil temperature on average by 15°C, but no statistical difference in soil moisture was found. Baryła et al. (2019) demonstrated that the surface temperature of green roofs is buffered compared to that of traditional roofs and that for a Mediterranean climate, the summer cooling effect was more beneficial than the buffering effect in winter. This was attributed to surface coverage and slow water uptake which kept moisture in the soil resulting in smaller fluctuations in temperature compared to drier soil. Heterogeneity of mineral and organic substrates was also investigated under a dry Mediterranean climate. Although some impact on vegetation was noticed in the first year, no statistically significant difference was found in plant diversity and biomass over three growing seasons (Vasl et al., 2019).

Although sedums are the most common plant type used on extensive green roofs, there is much interest in vetting plant choices for improved retention. A study comparing three broadleaf species to the industry standard sedum found that two of the three species (*Salvia* and *Stachys*) demonstrated the greatest retention due to high ET rates between rainfall events (Kemp, Hadley, & Blanusa, 2019). Canopy interception, which was greatest for the sedum, was found to be a statistically significant factor in retention but was less important than ET and overall substrate water storage. The climate and availability of water will have a species-specific impact on green roof vegetation. Although all plants demonstrate a reduction in water consumption under water deficit conditions, there are species beyond sedum that retain adequate appearance (color, shape, vigor, and flowering) during water scare conditions but have higher water use which may be more applicable to green roofs designed for stormwater management in the Mediterranean climate such as *Brachypodium phoenicoide* and *Limonium virgatum* (Azeñas, Janner, Medrano, & Gulias, 2019). In addition, if the roof is used as a place of leisure or recreation, sedums are not appropriate. Hu, Liu, Liu, Cao, Chen, and Wang (2019) explored the use of centipedegrass as a green roof alternative in China. The green roof demonstrated reasonable hydraulic performance at 47.4% runoff reduction with minimal irrigation demonstrating applicability to the climate. Native prairie grass was explored as a potential irrigated green roof species in north-central Kansas, USA, which has a hot summer climate (Köppen–Geiger climate classification). The prairie grass faired quite well under its native conditions and outcompeted the sedums which demonstrated poor survival and coverage (Liu et al., 2019).

The studies in the prior sections all focused on short-term, small-scale studies. However, survival of the initial plants and the overall diversity can vary significantly with time due to uncontrollable factors such as climate and controllable factors such as maintenance. An eight-year-old green roof in Michigan was analyzed for the long-term effect of substrate depth on plant community development (Vandegrift, Rowe, Cregg, & Liang, 2019). The roof consisted of three different substrate depths with an intentional distribution of 22 different plant species, primarily sedum species in the shallow depth with herbaceous perennials and grasses in the deeper substrates. After eight years, with an effort to avoid colonization of new plants, all of the sedum species were still present but only five herbaceous perennials and two grasses survived with *Allium cernuum* as the dominant species. Many species demonstrated an increase in coverage during the first few years, but it is hypothesized that a drought in 2016 significantly reduced the diversity of the roof. Thuring and Dunnett (2019) also saw a decrease in plant diversity on two unmanaged extensive green roofs in Stuttgart, Germany. Both roofs retained full plant coverage, but due to the unmanaged state, over 50% of the plants were new colonizing species. The result was a multilayered meadow with sedums providing ground cover.

Common themes and future work

Similar to previous years, efforts to quantify the benefits and costs of green roofs and studies of the specific structural components of green roofs continued. However, there appeared to be an increased recognition of the role of evapotranspiration in overall stormwater retention particularly in modeling efforts, suggesting it is a growing area of research. In addition, studies continued to highlight the complexity of predicting the quality of green roof runoff, particularly with respect to nutrient loads suggesting an opportunity for additional studies in substrate amendments.

Rainwater harvesting

Rainwater harvesting is the practice of capturing rainwater from impervious surfaces, typically rooftops, and storing it on site for later use. Common uses for the stored water include landscape irrigation and other outdoor use, toilet flushing, or laundry. From a stormwater perspective, this practice intercepts runoff from rooftops and other impervious surfaces before it can move downstream and impact receiving water through flooding and pollutant transport. In 2019, there were at least 17 articles on rainwater harvesting, ranging from water quantity and flooding, water quality, system design, spatial modeling for design optimization, and economics and lifecycle assessment.

Water quantity and flooding

Using rainwater harvesting for water quantity and flooding reduction was of interest to researchers in 2019, with five articles focusing on this topic. Specific realms of interest included using models and simulations to predict the future availability of water for harvesting and the effectiveness of rainwater harvesting systems to reduce flooding. Two studies focused primarily on the quantity of water and its relationship to the amount of rainfall. In Colorado, water rights disputes prohibit rainwater harvesting with exceptions for residential rain barrels and a pilot project program that allows centralized harvesting for new development. In new development, projects are allowed to capture a volume equal to predevelopment runoff losses. Because of these restrictions, a tool to calculate the daily allowable harvest was developed using soil parameters and precipitation data. Using simulations from 2010 to 2017 from the Colorado Front Range, researchers concluded that rainwater harvesting can supply up to 50 percent of the annual demand for traditional landscaping irrigation water (Gilliom, Bell, Hogue, & McCray, 2019). Another study looked at simulations of rainwater harvesting and the capability of short-term rainfall data to produce accurate long-term predictions (Soares Geraldi & Enedir, 2019). Using the Bayesian network methodology presented, results from short-term data and long-term data were found to be similar. Further, the average number of dry days per year was shown to be important when using short-term data.

Also related to water quantity, researchers investigated using rainwater harvesting as a means to reduce flooding. In Melbourne, Australia, researchers developed a semicontinuous simulation using a continuous mass balance simulation model (Jamali, Bach, & Deletic, 2019). This model takes antecedent rainfall conditions and usage of the rainwater harvesting tanks to predict the available storage of the tanks prior to each storm event. The results showed that rainwater harvesting is economically feasible and can reduce anticipated flood damage by up to 30 percent, though the tank performance is impacted by the temporal distribution of rainfall and availability of storage space in the tanks. Deitch and Feirer (2019) examined the impacts rainwater harvesting has had on the discharge in the Perdido River basin in Florida, United States. Using a GIS-based cumulative-effects model, researchers evaluated the flow reduction through the basin with a 1.5-year recurrence interval. They found that developed parcels storing rainwater, such as retired septic tanks and cisterns, could reduce the discharge by at least 20 percent (Deitch & Feirer, 2019). Finally, Freni and Liuzzo (2019) studied the reliability of rainwater harvesting systems used for toilet flushing in Sicily, Italy, for more than 400 single-family homes. The researchers created a flushing water demand pattern from consumption data, and a "yield-after-spillage" algorithm was used to simulate the daily water balance of the rainwater harvesting tanks. Ultimately, the researchers found that the efficacy of the tanks for flood reduction and toilet flushing is highly contingent upon the amount of rainfall.

Quality

Two articles discussed the relationship between rainwater harvesting and water quality in 2019. In Palestine, researchers looked at the pH, alkalinity, hardness, turbidity, total dissolved solids, nitrates, ammonia, chloride, and salinity of harvested water in a region where rainwater harvesting is common due to an inadequate and expensive water supply otherwise. They found that out of 100 samples, most were within World Health Organization (WHO) and Environmental Protection Agency (EPA) water quality standards (Al-Batsh et al., 2019). Similarly, in Bolivia rainwater harvesting tanks were monitored for 22 months. Samples had elevated arsenic concentrations because of nearby mining operations. Thus, the researchers recommended that arsenic become a standard parameter when performing water quality monitoring in rainwater harvesting systems (Quaghebuer et al., 2019).

System design

System design covers the physical design of the rainwater harvesting system. Ranging from using rainwater harvesting for recharging aquifers to adapting system design for climate change, designs this year were innovative. Research by Hussain, Hussain, Wu, and Abbas (2019) investigated the ability of rainwater harvesting to recharge the Lahore Aquifer in Lahore City, Pakistan. Because there is less need for irrigation in very urban areas, they stored the harvested water in the aquifer using recharge wells. They found that the use of recharge wells had a recharge capacity of 29.32 m^3/hr, and if filter material was added, there was a contaminant removal of 20%–30%. While much of the research about system design for rainwater harvesting is focused on optimizing tank size, Nnaji, Tenebe, and Emenike (2019) focused on optimizing the hopper and guttering. They found that the slope of the gutter and the footprint of the roof impact the hopper design the most (Nnaji et al., 2019). Using past and future rainfall data, Zhang, Zhang, Zhang, Yue, and Jing (2019) studied the impacts of future climate change on water saving and rainwater capture performance using rainwater harvesting systems in China. Increased rainfall positively affected water saving performance and negatively impacted the capture performance of the rainwater harvesting system. This negative relationship was due to the larger required tank size needed to maintain capture efficiency for larger rain events.

Spatial modeling for design optimization

A focus of rainwater harvesting research in 2019 was the spatial component of design optimization. Infrastructure and funds are often not available to do in situ testing to design and optimize rainwater harvesting systems. Across the globe, researchers used numerical and spatial models to determine optimal areas for rainwater harvesting. Palermo, Talarico, and Pirouz (2019) utilized numerical optimization to determine the ideal rainwater harvesting schemes to reduce surface water overflows into a combined sewer system through the use of TOPSIS and the rough set methods of multi-objective optimization. Another study by Pathak, Garg, Jato-Espino, and Lakshmi (2019) ranked sites by water demand, availability of stormwater, distance to end-use locations, as well as socioenvironmental concerns to create a spatial model. Using GIS, they were able to upload results to public domain websites for real-time viewing, therefore minimizing costs for decision-makers. Finally, due to a great lack in biophysical data and infrastructure, researchers in India used geospatial data and multiple-criteria decision analysis (MCDA) to quantify the potential of rainwater harvesting for specific regions (Singhai et al., 2019).

The optimal location of rainwater harvesting can be based on socioeconomic, environmental, and technical feasibility. To account for this, researchers in Australia developed a framework to determine where rainwater harvesting should be used or if another source of water is more appropriate (Dandy et al., 2019). At an urban scale, rainwater harvesting saving potential is calculated as the balance between the annual rainfall and annual water consumption.

Economics and life cycle assessment

The cost and economic feasibility of rainwater harvesting were the focus of three articles in 2019. Pacheco and Campos (2019) used real options analysis (ROA) to account for uncertainties in demand, rainfall, and water tariffs in estimating cost for rainwater harvesting. In Brunei, rainwater harvesting was determined to be unfeasible due to capital costs and water price. Researchers proposed a rebate on capital costs and raising the water price to make rainwater harvesting a viable option in Brunei (Abas & Mahlia, 2019). Ghimire et al. (2019) compared the economic feasibility and productivity of rainwater harvesting systems to air conditioning condensate harvesting (ACH) in San Francisco and Washington D.C., United States. Using a lifecycle assessment approach, they were able to determine that rainwater harvesting outperformed ACH on four-story buildings, ACH outperformed RWH on taller buildings, and a combined system was the most effective (Ghimire et al., 2019).

Common themes and future work

A large portion of the research published in 2019 concerned water quantity, specifically on sizing and locating the systems to optimize their use based on external constraints including climate and policy. Two studies investigated overall water quality, and the economics of rainwater harvesting was also the focus of multiple studies. It appears these topical areas will continue to drive future research, with the goal of optimization of rainwater harvesting systems for water quantity, water quality, and short-term and long-term costs.

Watershed-scale LID assessments

Efforts to understand and quantify the conditions and processes through which systems of stormwater control measures and LID practices regulate urban stormwater runoff at the catchment or watershed scale continued in 2019, with over 37 related studies published. The following sections provide an overview of field and modeling studies related to characterization and/or optimization of watershed-scale LID performance, followed by a review of studies focused on social dimensions of LID implementation and, finally, a summary of common themes throughout this collection of papers and implications to future work.

Field assessment

Two studies were identified in which the performance of watershed-scale LID practices was assessed through field measurements. Ma et al. (2019) studied transport and retention of particulates and associated pollutants through a 4.1-Ha study area in Wenling, China, one of the country's model "sponge cities" in which grassed swales and filter strips (representing 35% of the study area) were designed to disrupt direct hydraulic connections between roadways and receiving waters. They observed high retention for both particulates (90%) and associated heavy metals (70%), and that the practices were particularly effective for fine particulates (<10 μm). Li, Kazemi, Kazemi, and Rockaway (2019) determined that a network of LID practices installed across a 111-Ha campus in Louisville, KY, reduced runoff volume and peak flows by 33% (22% *SD*) and 61% (28% *SD*), respectively, postinstallation. They also demonstrated the potential to use data-driven artificial neural networks (ANN) to predict LID performance in the absence of detailed drainage network or other watershed information.

Modeling assessment and optimization

In the absence of field studies, modeling studies are useful indicators of the potential to moderate urban stormwater runoff through watershed-scale implementation of LID practices. Li et al. (2019) used the stormwater management model (SWMM) to demonstrate that LID practices installed at a 64.6-Ha sports complex in Nanning, China, could reduce runoff volumes up to 19% while reducing TSS, COD, TN, and TP mass loads by 16% to 23%. Guo, Du, Du, Zhao, and Li (2019) also utilized SWMM to assess watershed-scale LID performance and presented a methodological framework for representing LID practices as both discrete elements and indirectly via adjusting watershed parameters. In a more emergent research area, Wolfand et al. (2019) assessed the potential to retain pesticides (fipronil and pyrethroids) in bioretention systems with and without biochar amendments if implemented across the watershed. Their results indicated over 80% of assessed pesticides and degradation products could be retained in unlined bioretention systems amended with biochar, while as little as 26% may be retained in noninfiltrating bioretention systems with conventional media.

Random placement of LID practices throughout urban watersheds is likely to be less effective than strategically siting LID practices to ensure hydrologic connections with runoff and pollutant source areas. For example, Epps and Hathaway (2019) used SWMM to demonstrate that siting LID practices (here, bioretention or pervious areas) to intercept runoff from impervious areas with direct connections to drainage infrastructure improved median volume capture by approximately 10% (from 30% to 40%) relative to random placement. However, the difference between random and strategic siting was not significant when only storms greater than 12 mm were considered in their study watershed in Knoxville, TN. Multiple studies coupled various optimization algorithms with SWMM to identify optimal LID solution sets in which hydrologic, water quality, and/or cost functions were optimized. For example, the nondominated sorting genetic algorithm was used to minimize LID network costs while maximizing PCB removal (Wu et al., 2019), the multi-objective shuffled frog-leaping algorithm was applied to find optimal LID solutions for COD reductions at minimal cost (Liu, Chen, Chen, Shen, Xiao, & Wei, 2019), the PEST algorithm was employed to identify optimal sets of LID practice design parameters to meet target runoff hydrographs (Zhu, Chen, Chen, & Yu, 2019), and the recently developed multi-objective antlion optimization algorithm was found to outperform other optimization methods in minimizing flooding, runoff volume, economic cost, and long-term performance reductions associated with clogging (Mani, Bozorg-Haddad, & Loáiciga, 2019). Lu and Qin (2019) aimed to address uncertainties associated with hydrologic modeling by coupling a fuzzy simulation optimization model with SWMM to identify optimal combinations of green roof, bioretention, and permeable pavement required to achieve various confidence levels of flood control. While promising, the method was computationally expensive. In addition to model and parameter uncertainty, uncertainty in future land use may also be important to consider in LID simulation optimization models. Bahrami, Bozorg-Haddad, and Loáiciga (2019) demonstrated the potential to couple a genetic algorithm with SWMM to assess sensitivity of runoff reductions by optimal LID sets to plausible future development scenarios. Finally, a novel optimization framework presented by Latifi, Rakhshandehroo, Nikoo, and Sadegh (2019) incorporated a leader–follower game-theoretical model to identify optimal watershed-scale LID solutions in which the actions of key stakeholder groups (e.g., environmental agencies, municipalities, and utilities) are incorporated. Computational demands in this modeling framework were reduced by replacing hydrologic model simulations (here, SWMM) with an artificial neural network.

The potential to utilize LID practices to moderate the effects of climate change on watershed hydrologic responses continues to be an area of active research. Sohn, Kim, Li, and Brown (2019) presented a review of recent studies in which resilience of LID systems to future climate scenarios was assessed. Their review highlighted a general agreement that LID systems can still be expected to maintain runoff volumes below current baseline (i.e., conventional urban development) levels, though design adaptations may be necessary to enable vegetated LID systems to withstand longer drought periods (e.g., deeper substrates). Runoff volumes from a LID watershed (1.2 km^2) were compared with those from a conventionally developed watershed (3.1 km^2) in the Chesapeake Bay region (USA) under future climate (as predicted by two different emissions scenarios within two different global climate models, or GCMs) using a daily time step continuous hydrologic model (Giese, Rockler, Shirmohammadi, & Pavao-Zuckerman, 2019). The runoff response from the LID watershed was muted relative to the traditionally developed watershed for all but the largest of storms (>60 mm) and was also sensitive to seasonal changes in precipitation distributions. Citing the high variability among various GCMs (and associated variability in the design of LID practices to effectively treat future watershed runoff regimes), Zhang, Manuelpillai, Manuelpillai, Raut, Deletic, and Bach (2019) demonstrated the need to consider an ensemble of climate models (as opposed to multiple scenarios from a single GCM) for assessing the robustness of LID systems in climate change studies. In addition to changes in precipitation magnitude and frequency, effects of changing climate on antecedent soil moisture (AMC) may also be important when assessing future LID performance at the watershed scale. Using a case study in St. Paul, MN, as an example, Hettiarachchi, Wasko, and Sharma (2019) demonstrated that warmer temperatures and associated trends in rainfall characteristics may reduce AMC such that pervious surfaces and LID systems throughout a watershed have greater storage capacity through which to mitigate future runoff events. This result points to the need to adopt continuous models or other methods to adequately capture the effects of AMC on watershed runoff responses. In another study, a set of LID performance metrics reflecting adaptability of LID systems to manage a range of runoff events was proposed (Song, Yang, Yang, Chang, Li, & Wu, 2019). While this study did not specifically address climate change, the set of adaptive indicators may be useful in future climate studies.

The primary metrics through which LID performance has been assessed and/or optimized include runoff volume, peak flow, runoff load reductions, and/or economic costs. While such metrics are informative, they do not necessarily reveal potential damage to urban infrastructure or ecosystems. Two studies were identified in which watershed hydrologic models were used to develop impact-based metrics for assessing LID performance. Vercruysse et al. (2019) presented a method by which to prioritize LID and flood management practices according to criteria that characterized both the extent of flooding and the type of infrastructure impacted via a spatially explicit hydrodynamic urban flood model (CityCAT). While the authors note that further development is needed, their method offers a means to systematically assess hydrologic connections between areas impacted by flooding and the areas that contribute the most to these impacts. A set of ecohydraulic metrics—including channel flow regimes, channel bed mobility, hydraulic diversity, and retentive habitat availability—were proposed by Anim et al. (2019) to better represent the effects of urban runoff on receiving stream systems. In an application of these metrics to a 40-km^2 watershed near Melbourne, Australia, the authors demonstrated that maintaining these metrics near predevelopment conditions would require intensive LID implementation, in this case such that total postdevelopment runoff was reduced by 65%.

As demonstrated by several studies in 2019, the hydrologic functions performed by LID systems can be linked to provision of a suite of other cobenefits or ecosystem services (Alves, Gersonius, Kapelan, Vojinovic, & Sanchez, 2019; Radinja, Comas, Corominas, & Atanasova, 2019; Rai, Minsker, Sullivan, & Band, 2019; Sohn et al., 2019; Venkataramanan et al., 2019). In a review by Zhang and Chui (2019), the scale-dependent nature of cobenefits provided by LID, as well as the current paucity of experimental studies to better characterize such cobenefits, was highlighted. Other advances in quantifying LID cobenefits included the use of remotely sensed Landsat-8 thermal infrared data to assess thermal benefits provided by green spaces in Yinchuan City, China (Hou, Mao, Mao, Li, & Sun, 2019), and a novel computational framework in which a process-based hydrologic model (RHESSys) and a machine learning human preference model were coupled to quantitatively consider both hydrologic performance requirements and human well-being (Rai et al., 2019). To facilitate selection of LID systems across multiple cobenefit categories, studies demonstrated the utility of various decision analysis frameworks including multicriteria analyses (Alves et al., 2019; Radinja et al., 2019), analytical hierarchy process (Li et al., 2019), and TOPSIS (Luan et al., 2019).

Implications to watershed-scale planning and assessment

As indicated throughout the previous section, watershed-scale assessments of LID performance continue to indicate the potential to moderate the deleterious effects of urban runoff on downstream ecosystems while reducing localized flooding within the watershed and providing a range of other environmental and social benefits. However, experimental studies lag, in part, because there are few instances of watershed-scale LID implementation, and even fewer in which implementation follows optimal patterns according to, for instance, optimization studies described in the previous section. Numerous studies published in 2019 were aimed to better understand factors constraining current LID implementation and opportunities to advance watershed-scale implementation. For example, an analysis of landscape and socioeconomic factors associated with LID implementation in Portland, OR, and Baltimore, MD, demonstrated that past policy and initiatives related to stormwater management can manifest in very different and sometimes unexpected spatial distributions of LID practices (Baker, Brenneman, Chang, McPhillips, & Matsler, 2019). A content analysis of stormwater-related policies throughout cities in Canada revealed that 4 of the country's 10 provinces were "highly LID friendly," though an analysis of actual LID implementation under such policies was outside the scope of this analysis (Ishaq, Hewage, Farooq, & Sadiq, 2019). Local implementation of LID practices in relation to a set of governance factors was investigated by Qiao, Liu, Kristoffersson, and Randrup (2019) who found divergent governance drivers through analysis of case study cities in China (where national policy and strong organizational structure drove LID adoption) and Sweden (where local priorities, public awareness, and trust in LID performance drove adoption).

The role of individual actors in LID adoption and implementation was also considered. For example, Chaffin, Floyd, and Albro (2019) considered the question "what network qualities characterize peer-nominated leaders in informal, multi-organizational networks for stormwater management?" through analyzing the social networks of LID professionals in Cleveland, OH, the identified network size, frequency of collaborations, and position within the network as important characteristics. In this particular case, women were more likely to hold leadership roles within the informal, multi-institutional networks through which LID policy and practices were implemented. The importance of community participation to implement LID practices was demonstrated through a case study of an urban watershed in Atlanta, GA (Barclay & Klotz, 2019). The importance of community education in combating common social barriers such as resistance to change was highlighted. Such community education efforts should emphasize provision of cultural-based ecosystem services provided by LID and green infrastructure networks alongside environmental benefits since the former may be more highly valued by community members (Miller & Montalto, 2019).

Differences in policy, governance structures, and values of the networks of actors overseeing LID implementation will likely require a more nuanced approach to identifying "optimal" solutions to manage stormwater runoff more sustainably in cities across the globe. Incorporation of social-based models in more traditional biophysical optimization frameworks, such as the game-theoretical model explored by Latifi et al. (2019), may be helpful in this effort. Other decision support tools in which decision-makers and other stakeholders are deeply embedded were also represented in the literature in 2019 (Fu, Hopton, Wang, Goddard, & Liu, 2019; Ibrahim, 2019; Kuller, Bach, Roberts, Browne, & Deletic, 2019; Leonard et al., 2019). For example, Kuller et al. (2019) presented a novel suitability framework in which potential sites for LID implementation were conceptualized as needs and opportunities, where needs were defined as ecosystem services and opportunities as a combination of socioeconomic, planning, and governance criteria. The potential to enhance participatory planning efforts among stormwater professionals, decision-makers, and/or property owners through the use of web applications (here, Jupyter Notebook) to rapidly create visualizations and generate ecohydrologic metrics for site-scale LID designs is also demonstrated (Leonard et al., 2019). Tools such as these are essential to advance LID implementation at the watershed scale.

Common themes and future work

Watershed-scale runoff volume management is essential to maintain and/or restore flow regimes and pollutant concentrations that are supportive of aquatic habitat and biota. Studies published in 2019 indicate that LID practices can achieve various hydrologic and water quality targets when implemented extensively throughout urban watersheds, and various optimization and decision support tools were developed to facilitate optimal siting of such practices. Common themes arising through this review included the need to better address uncertainty in watershed models as well as in the design parameters through which LID elements are represented in both watershed-scale performance and optimization studies. This review also highlighted current efforts to understand the adaptive capacity of urban watersheds and LID systems to future climate changes. Current work has focused largely on the capacity for these systems to mitigate increasingly extreme events; future work is needed to understand responses to shifts in the timing of precipitation events as well as other climate factors (e.g., through continuous simulation) and to examine the robustness of LID designs against the backdrop of large uncertainties in climate science. Finally, the potential for LID practices to provide multiple environmental and social cobenefits in addition to stormwater regulation was a recurring theme throughout watershed-scale LID literature published in 2019. The call to incorporate such cobenefits in a more meaningful way in LID planning and optimization tools also emerged repeatedly, as did the need to address the paucity of experimental data—particularly with respect to social cobenefits—that could underpin more meaningful inclusion in LID performance metrics.

Table 1. Number of articles in each category for "Urban Stormwater Characterization, Control, and Treatment" between 2015 and 2019 (Moore et al., 2018; Moore et al., 2017; Rodak et al., 2019; Vogel & Moore, 2016; this issue)

	NUMBER OF ARTICLES									
YEAR	GENERAL STORMWATER	EROSION AND SEDIMENT CONTROL	STORMWATER PONDS	CONSTRUCTED STORMWATER WETLANDS	BIORETENTION	PERMEABLE PAVEMENT	GREEN ROOFS	RAINWATER HARVESTING	WATERSHED-SCALE ASSESSMENT	OTHER
2015	40	10	15	15	33	18	70	15	11	3
2016	42	11	19	19	49	20	18	15	20	14
2017	50	6	21	26	40	33	20	25	10	0
2018	25	12	17	23	37	30	33	13	42	10
2019	42	9	23	17	55	38	36	17	37	7
Mean	40	10	19	20	43	28	35	17	24	7
Median	42	10	19	19	40	30	33	15	20	7

Table 2. Subtopics in each category for "Urban Stormwater Characterization, Control, and Treatment" between 2015 and 2019 (Moore et al., 2018; Moore et al., 2017; Rodak et al., 2019; Vogel & Moore, 2016; this issue)

	SUBSECTIONS								
YEAR	GENERAL STORMWATER	EROSION AND SEDIMENT CONTROL	STORMWATER PONDS	CONSTRUCTED STORMWATER WETLANDS	BIORETENTION	PERMEABLE PAVEMENT	GREEN ROOFS	RAINWATER HARVESTING	WATERSHED-SCALE ASSESSMENT
2015	Stormwater quantity, stormwater quality	Sediment control, inspection, and modeling	Water quality, design for optimization	Field, laboratory, and modeling performance studies; design optimization and innovations; floating treatment wetlands	Field, laboratory, and modeling performance studies; enhanced media; vegetation; design innovations; environmental impacts and other benefits	Hydraulics and related properties, modeling, water quality, innovations	Water quality; field, laboratory, and modeling performance studies; vegetation	Water quality, design optimization, economics and ecosystem services	Watershed-scale LID optimization, implications to watershed-scale planning and implementation
2016	Quantity, quality	Erosion control, sediment control	Water quality, design and management for optimization	Field, Laboratory, and modeling performance; longer-term performance; design optimization and innovations; floating treatment wetlands	Field, Laboratory, and modeling performance studies; enhanced media; vegetation and other biota; environmental impacts and other benefits	Hydraulics and related properties, modeling, water quality, innovation	Field, laboratory, and modeling performance studies; water quality and substrate amendments; vegetation	Water quality, design optimization, economics and ecosystem services	Field assessment, modeling assessment and optimization, implications to watershed-scale planning and implementation
2017	Quantity, quality	Erosion control, sediment control	Water quality, design and management for optimization	Field, laboratory, and modeling performance; longer-term performance; design optimization and innovations; floating treatment wetlands	Field, laboratory, and modeling performance studies; enhanced media; vegetation and other biota	Hydraulics and related properties, modeling, water quality, innovation	Field, laboratory, and modeling performance studies; water quality and substrate amendments; vegetation	Quality, design optimization, economics and ecosystem services	Field assessment, modeling assessment and optimization, implications to watershed-scale planning and implementation
2018	Quantity, quality	Erosion control, sediment control	Water quality, design and management for optimization	Field, laboratory, and modeling performance studies; longer-term performance; design optimization and innovations; floating treatment wetlands	Field, laboratory, and modeling performance studies; enhanced media; vegetation and other biota	Hydraulics and related properties, modeling, water quality, innovations	Field, laboratory, and modeling performance studies; water quality and substrate amendments; vegetation	Quality, design optimization, economics and ecosystem services	Field assessment, modeling assessment and optimization, implications to watershed-scale planning and implementation

(Continues)

Table 2. (Continued)

	SUBSECTIONS								
YEAR	GENERAL STORMWATER	EROSION AND SEDIMENT CONTROL	STORMWATER PONDS	CONSTRUCTED STORMWATER WETLANDS	BIORETENTION	PERMEABLE PAVEMENT	GREEN ROOFS	RAINWATER HARVESTING	WATERSHED-SCALE ASSESSMENT
2019	Quantity, quality	Erosion control, sediment control, inspection, and modeling	Water quality, biodiversity, design and management for optimization	Field, laboratory, and modeling performance studies; longer-term performance; design optimization and innovations; floating treatment wetlands	Field, laboratory, and modeling performance studies; enhanced media; vegetation, trees, and other biota; reviews	Hydraulics and related properties, modeling, water quality, innovations	Field, laboratory, and modeling performance studies; water quality and substrate amendments; vegetation	Water quantity and flooding, quality, system design, spatial modeling for optimization, economics and life cycle assessment	Field assessment, modeling assessment and optimization, implications to watershed-scale planning and implementation

Other

Seven studies were conducted in 2019 that did not fall into one of the categories presented in the preceding sections, but highlighted important findings. The topics fall into two general categories of treatment trains and novel substrates and innovative monitoring and assessment.

Treatment trains and novel substrates

The use of pilot units was important in 2019, as researchers sought to understand the efficacy of filtration systems and amended media in treatment performance. A pilot-scale study was conducted in Cheongju, Korea, to evaluate a stormwater filtration system and determine implications of variables such as coagulant usage on efficacy. The 280,000 cubic meter per day pilot unit included hydrocyclones, a filter column, backwash tower, and other appurtenances. Influent and effluent suspended solids were measured after simulated stormwater events. Results highlighted improved removal efficiency of the pilot unit was achieved when polyaluminum chloride silicate was used and that particulate effluent sizes were larger than influent when the coagulant was used for treatment (Lee, Lee, & Lee, 2019).

Researchers employed a set of column tests to evaluate biochar-amended wood chip's performance to remove nutrients, metals, and trace organic contaminants as compared to wood chips alone and wood chips and straw. Compared to wood chips alone, columns with wood chips and biochar had improved removal of trace organic contaminants while performing similarly in removing nitrate, cadmium, copper, nickel, and lead (Ashoori et al., 2019).

The coating of montmorillonite clay composites and the clays' subsequent use for stormwater infiltration efforts were the focus of a study that included polymer–clay composite synthesis and batch sorption experiments. The montmorillonite clay was functionalized using either poly(diallyldimethylammonium) chloride (PDADMAC) or poly(4-vinylpyridine-co-styrene) (PVPcoS). Compared to biochar, the polymer–clay composites showed similar performance in perfluoroalkyl substance removal, improved performance in oxyanion removal, and decreased performance in trace organic removal (Ray, Shabtai, Teixidó, Mishael, & Sedlak, 2019). The evaluation of engineered sand was the foci of other researchers' studies where phosphate, zinc, caffeine, and *E. coli* reduction were evaluated. The engineered sand was obtained using thermal treatment using an Al-Mg/GO solution. Flow experiments showed more retention of *E. coli* in engineered sand versus raw sand and with a stronger antibacterial activity in the former (Vu & Wu, 2019).

Innovative monitoring and assessment

McDonald (2019) provided a review of the use of drones in urban stormwater monitoring and management. Drones have the ability to monitor regions not easily accessible to their human counterparts. The use of drones is expected to increase as they can provide high-resolution information which can be used for model parameterization, flow and water quality monitoring (e.g., multispectral data), and overall asset management.

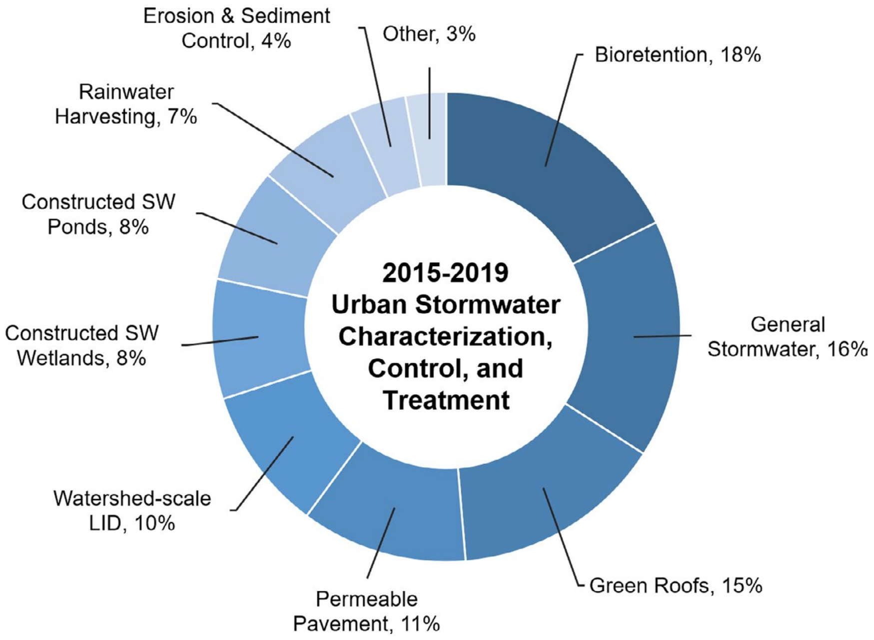

Figure 1. Contribution of literature in each subtopic for "Urban Stormwater Characterization, Control, and Treatment" between 2015 and 2019 (Moore et al., 2018; Moore et al., 2017; Rodak et al., 2019; Vogel & Moore, 2016; this issue).

Two studies conducted in 2019 evaluated the cost implications of stormwater management. A study conducted in Brazil evaluated small municipalities (1,000–20,000 residents) comparing the use of the Equivalent Residential Unit (ERU) system to a Simplified Equivalent Residential Unit (SERU) system to determine a stormwater user fee for operations and maintenance. The SERU, which was based on impervious areas of urban lots and the number of urban lots in a city, was found to require fewer resources and can therefore be a useful metric for areas that do not have complex stormwater management in place (Tasca, Finotti, Goerl, & Tasca, 2019). A paper published in 2019 asked the question "is a stormwater fee a rain tax?" to discuss the unique financing of stormwater management. Stormwater fees are being employed by local governments, but there is significant resistance to fees and scrutiny on how to assess performance. The paper highlights the need transparency regarding how these funds are being used (Grigg, 2019).

Common themes and future work

The use of engineered or modified materials is shown to be an area of heightened interest as it looks to identify ways to potentially optimize existing infrastructure/systems by modifying media that is used within these systems. In addition, the use of drones in stormwater management is expected to increase as their use becomes more ubiquitous. Finally, as funding continues to be a critical factor in addressing stormwater, the identification of best practices in identifying fees as well as translating how funds are spent to address stormwater becomes increasingly important.

Five-year research trends

Including this year's review, this author group has completed the "Urban Stormwater Characterization, Control, and Treatment" literature review for the last five years covering over 1,200 papers (Moore, Rodak, Ahmed, & Vogel, 2018; Moore, Rodak, & Vogel, 2017; Rodak et al., 2019; Vogel & Moore, 2016; this issue). As a result, we have a unique perspective to elucidate general trends within the topic of urban stormwater. In general, research topics, distribution of papers among topics, and category subtopics have been relatively consistent for the past five years (Tables 1 and 2) with a general increase in the total number of papers reviewed. The categories "General Stormwater" and "Bioretention" have consistently had the most papers each representing between 15% and 22% of the reviewed literature each year, while "Erosion and Sediment Control" has had the fewest average amount of papers, between 3% and 5% of the total reviewed papers each year (Figure 1). "Green roofs" experienced an initial decrease from 2015 where it had more papers than any other topic but has increased in recent years. The number of "Permeable Pavement" and "Watershed-scale Assessment" papers has increased between 2015 and 2019 (Table 1). Similar to the topics, the subtopics within each broader topic category have also remained relatively consistent during this period (Table 2). Notable additions include a multiyear increase in papers on biodiversity in stormwater ponds such that a separate section was created in 2019, fewer papers dedicated solely to ecosystem services in bioretention during the last three years, and research on amendments in green roof media from 2016 through 2019.

Conclusions

In 2019, the topic of stormwater characterization, control, and treatment remained a highly active area of research. Studies reviewed ranged from fundamental mechanistic studies to watershed-scale assessment of the effectiveness of stormwater management. The role of vegetation on stormwater and pollutant uptake as well as the use of novel substrate amendments was present across several different SCMs suggesting cross-fertilization of findings may have fruitful outcomes. Also common in the literature was the use of models (frequently SWMM) to quantify stormwater rainfall–runoff behavior in urban systems and individual SCMs. SWMM was also used in several quality models which on average struggled with accuracy and replication of field data more so than their hydrologic counterparts. This suggests water quality modeling, and the mechanisms, which underly pollutant transport in urban watersheds and SCMs, will be a critical area of continued research interest likely to overlap with the growing use of machine learning. Finally, there continues to be a push to develop models and decision support systems which can incorporate the physical–social–economic constraints of LID and general stormwater management practices.

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