Urban Stormwater Characterization, Control, and Treatment

Trisha L. Moore[1*], Carolyn M. Rodak[2], Jason R. Vogel[3]

ABSTRACT: A summary of 246 studies published in 2016 on topics related to the characterization and management of urban stormwater runoff is presented in the following review. The review is structured along three major topical areas: (1) general characterization of stormwater quantity and quality; (2) engineered systems for stormwater control and treatment, including erosion and sediment control practices, constructed stormwater ponds and wetlands, bioretention, permeable pavement, greenroofs, and rainwater harvesting and (3) watershed-scale application of stormwater treatment and control practices. Common research themes and needs highlighted throughout this review include efforts to better understand stormwater transport and treatment mechanisms and their representation in models, advancements to optimize the design of stormwater control measures to meet specific hydrologic and/or water quality targets, and increasing understanding of the biophysical and social factors that influence watershed-scale implementation of low impact development and other stormwater control measures.

[1*]Biological and Agricultural Engineering, 920 N. 17th, Kansas State University, Manhattan, Kansas, 66506; Tel. 785-532-2911; Fax. 785-532-5825; e-mail: tlcmoore@ksu.edu.

[2]State University of New York Polytechnic Institute, Civil Engineering, Utica, New York

[3]Oklahoma State University, Biosystems and Agricultural Engineering, Stillwater, Oklahoma

KEYWORDS: low impact development, stormwater control measures, runoff, water quality, hydrology

doi: 10.2175/106143017X15023776270692

Introduction

Urban stormwater runoff is recognized as a leading cause of degradation in streams and other aquatic ecosystems. The impacts of stormwater runoff – which include increased flood frequency, streambank erosion, eutrophication, habitat loss, and acute or chronic toxicity to aquatic biota – are a direct result of changes in the quantity, frequency, and quality of surface runoff following increases in impervious surface cover and hydraulic expediency that accompany urbanization. To mitigate these impacts, a variety of engineered and non-structural stormwater control practices and systems may be employed. These practices are known under a variety of different terms, including stormwater control measures (SCMs), best management practices (BMPs), water sensitive urban design (WSUD), sustainable urban drainage systems (SUDS), green infrastructure (GI) and low impact design (LID). For consistency with Vogel and Moore (2016) and to avoid confusion by readers, the general phrase "stormwater treatment and control practices" is adopted throughout this review, along with LID, which, for the purpose of this review, is used to refer to any system of stormwater treatment and control practices in which natural processes are employed to manage stormwater at its source.

The objective of this paper is to provide a comprehensive review of the literature published in 2016 on the topics of urban stormwater control and treatment. This review follows the same organization as Vogel and Moore (2016), beginning with an overview of general stormwater quality and quantity characteristics, followed by a summary of studies published regarding seven of the most common engineered stormwater treatment and control practices (erosion and sediment control, constructed stormwater ponds, constructed stormwater wetlands, bioretention, permeable pavement, greenroofs, and rainwater harvesting), and then a review of studies assessing application and/or optimization of stormwater treatment and control practices at the watershed scale. Finally, a set of papers that filled innovative research niches outside of the aforementioned categories is reviewed, followed by a summary of research themes and needs to continue the advancement of stormwater treatment and control.

General Stormwater

An understanding of stormwater quantity and quality in urban settings is critical for the design and implementation of effective stormwater controls and treatment methods (Zhang, Che et al., 2016). Data collection and analysis can provide information on current stormwater conditions and behavior. These data also support the construction of predictive stormwater quantity and quality models, which can be an important tool for understanding stormwater behavior under unobserved and/or changing conditions.

Quantity. The accuracy of rainfall-runoff models relies heavily on proper parameterization. Ajmal et al. (2016) continued to build on their 2015 work focusing on the applicability of the Natural Resources Conservation Service (NRCS) model for forested steep slope runoff by recommending a modified initial abstraction parameter which improved overall model performance with statistically significant improvement in 35 of 39 tested watersheds. In highly urbanized watersheds, Ebrahimian et al. (2016) focused on improving the performance of rainfall-runoff models through more precise estimation of the effective impervious area (EIA) via a successive weighted least square (WLS) method. The WLS method was used to estimate EIA for 50 basins and the ratio of EIA to total impervious area (EIA/TIA) for 42 residential basins. Although the authors identified statistics for EIA/TIA in residential basins, they caution against the use of the mean EIA/TIA ratio to predict EIA in ungauged basins due to high variability in EIA/TIA resulting in low statistical confidence in the mean EIA/TIA ratio.

In addition to parameterization, the impact of green space type, geometry, and connectivity on runoff quantity was investigated (Donovan et al., 2016; Kim and

Park, 2016). The role of landscape configuration on peak runoff was examined in four metropolitan areas of Texas using a least square regression analysis (Kim and Park, 2016). Large, clustered, and connected patches of vegetation were found to be likely to reduce peak flows versus small, fragmented, and isolated green space. In Portland, Oregon, Donovan et al. (2016) also investigated the impact of vegetation on peak flows and discovered low ground cover had a statistically relevant impact on stormwater runoff peak flow in the summer. However, they found no statistically significant impact of trees (high cover) on summer or winter peak flows, nor did they find any impact of low ground cover in winter, suggesting additional statistical analysis of intact basins is needed to truly understand the impact of green space on stormwater quantity at the urban catchment scale.

Application and development of computational models for stormwater quantity is reliant on the amount and resolution of data available. While most do focus on the physical behavior of the system, physical models tend to perform poorly when predicting extreme events such as flooding Gaitan et al. (2016) analyzed openly available socioeconomic and environmental datasets in Amsterdam, Netherlands by multiple linear regression (MLR) and found that imperviousness and distance to the watershed outlet were the only strong predictors of flood complaints by residents. Interestingly, areas close to watershed outflows were more prone to flooding suggesting surface flooding, overloading, or backwater effects are the cause of the flooding. In addition to difficulty describing extreme events, physical models are usually data intensive. Pina et al. (2016) demonstrated the importance of data availability when comparing the application of semi-distributed (SD) and fully-distributed (FD) models for the prediction of flooding in two case studies: 1.5 km^2 flat watershed with insufficient inlet capacity in Portugal and an 8.5 km^2 flat watershed with surface ponding in the United Kingdom. The SD model outperformed the FD model in both case studies, where the FD models overestimated surface storage due to insufficient data availability and refinement. However, when data are available to properly calibrate and validate FD models such as stormwater runoff modeling system (SWARM) models and the stormwater management models (SWMM), their predictive capabilities can inform decisions related to future land use and climate conditions (Abdul-Aziz and Al-Amin, 2016; Blair and Sanger, 2016). Changes in stormwater runoff due to increased imperviousness and potential changes in precipitation patterns occur on different time scales and the impact of multiple changes in a watershed is not additive. Therefore, it is essential that predictive stormwater quantity models consider the combinatory impact of land use and climate change possibilities.

Quality. Stormwater runoff carries with it a diverse set of contaminants including, but not limited to suspended solids, heavy metals, polycyclic aromatic hydrocarbons (PAHs) and various nutrients. Understanding the processes responsible for contaminant transport is of particular importance in stormwater quality modeling. The modeling of build-up and wash-off processes in urban catchments was a focus of several studies in 2016. Some researchers built and demonstrated their own models, such as MEDUSA (Modelled Estimates of Discharges for Urban Stormwater Assessments) created by Fraga et al. (2016). Hong, Bonhomme, Le, and Chebbo (2016) applied the physically-based FullSWOF and Hairsine-Rose (HR) models to the build-up and wash-off of total suspended solids (TSS) in a small road catchment. Raindrop-driven detachment was identified as the primary process responsible for TSS wash-off and transport during the first part of a rainstorm. Qin et al. (2016) also focused on the wash-off process and developed a logistic wash-off model which assumes contaminant loads available for wash-off increase with cumulative runoff volume following a logistic curve (S-shaped curve). The logistic wash-off model predicted first, middle, and last flush behavior better than the commonly used exponential model though the authors caution this may be due to two additional calibration parameters for the logistic model. Al Ali et al. (2016) investigated the performance of the exponential build-up model in SWMM and a power function for build-up. SWMM performed well in short term, single-event conditions but failed to replicate long term trends in TSS transport; ultimately neither model could not be adequately calibrated to produce acceptable results. Chunlin et al. (2016) also explored the use of SWMM to model water quality and quantity concerns in a highly-urbanized basin. While water quantity behavior was fairly well described, water quality modeling was less successful with specific difficulty in reproducing total phosphorus concentrations. Hong, Bonhomme, and Ghassan (2016) had a similar issue when demonstrating the TRENOE model consisting of a 2D physically-based TREX model and 1D conceptual CANOE model. Although the model adequately depicted water quantity behavior in a 0.12 km^2 basin, the researchers were unable to adequately model water quality, likely due to the importance of raindrop-driven detachment of TSS in the wash-off processes. The search for appropriate models to describe build-up and wash-off processes indicates an uncertainty as to how to model the physical processes involved. Although several authors identified raindrop-driven detachment as a driving force in water quality modeling, Wijesiri et al. (2016a) demonstrated that the uncertainty in wash-off models is actually less significant to the overall model results than uncertainty in the contaminant build-up process suggesting additional research to understand and model build-up processes would have the greatest impact on improving water quality models.

Analysis of heavy metal loads in stormwater runoff over the past 30 years produced little evidence of increasing metal concentrations with increasing urbanization. There is evidence of global-scale decreases in lead (Pb) but other observed changes in heavy metal concentrations, such as chromium (Cr) and copper (Cu), are likely due to site-specific factors (Sharley et al., 2016). One source of heavy metal contamination is stormwater runoff from various impervious surfaces. Charters et al. (2016) compared heavy metal and TSS loads from three roofs and one roadway and found that TSS transport from roofs was source limited while TSS and heavy metal transport from roadways is transport limited, thus indicating significant build-up of TSS and metal availability on the roadways. Similar results for TSS wash-off from impervious surfaces were also reported by Leutnant et al. (2016); TSS wash-off from roof sources was determined to be source limited while parking lot and street runoff was transport limited. The researchers suggest stormwater quality models need to account for differences in transport and source limited behavior.

In an effort to explain the variability observed in metal loads, several researchers investigated correlations between heavy metal loads and traffic parameters and hydrological conditions in 2016. The most commonly reported correlations were between heavy metal loads and traffic volume, antecedent dry period (ADP), and land use type. Percot et al. (2016) utilized a new method to assess the contribution of atmospheric deposition of heavy metals and determined atmospheric deposition was not a significant contributor to heavy metal loads in a small catchment in France, likely due to lack of industrial development in the catchment. Liu, Gunawardana, et al. (2016) identified traffic volume as the most critical parameter for heavy metal build-up on urban roads followed by land use, proximity to arterial roads, ADP, and road surface roughness. This study also reported decreasing variability in heavy metal build-up with increasing traffic volume. Huber and Helmreich (2016) analyzed heavy metal contamination at 45 sites and determined the most common metals present were Cu, Pb, and zinc (Zn). Cadmium (Cd), Cr, and Cu, loads were also found to correlate with average daily traffic but only Cd showed a correlation with annual rainfall depths. To investigate correlations between rainfall and heavy metal concentrations in runoff, Schiff et al. (2016) physically simulated varying rainfall conditions over a parking lot and measured TSS, heavy metals and PAH concentrations in the parking lot runoff. The mean concentrations were inversely correlated with storm duration and intensity, likely a result of dilution. Huber, Welker and Helmreich (2016) completed a compilation of 294 sites and, in addition to weak correlations between heavy metals and precipitation factors, also found the ADP was a statistically significant predictor of heavy metals. Shen et al. (2016) also saw a positive correlation between ADP and heavy metal loads in the surface dust of urban roads and roofs in Beijing China. In addition, the dust from urban roads with small grain sizes had higher pollutant concentrations. Wijesiri et al. (2016b) also found that the majority of heavy metals in build-up and wash-off were present in the fine fraction (<150 μm) with a few anomalies corresponding to ADP of 7-8 days. Therefore, water quality models that account for TSS particle size distributions, such as that proposed by Thompson et al. (2016), represent a step forward in modeling TSS and heavy metal loads in stormwater runoff.

To determine the potential leaching of heavy metals from sediment, dust samples from seven sites in Sweden were collected, characterized, combined with synthetic rainwater and agitated at varying levels (Borris et al., 2016). Metal concentrations in the liquid phase were found to be dependent on site characteristics such as traffic intensity, particle properties such as organic matter content, and runoff characteristics such as agitation intensity. Though the majority of the metals remained in particulate forms, SEM and energy dispersive X-ray microanalysis by Djukić et al. (2016) showed no presence of heavy metals on the solid particles. This suggests transport of metals in runoff may be due to precipitation processes and not adsorption. However, due to the correlation between heavy metals and TSS, TSS has been used as a surrogate for determining heavy metal loads in models. Trenouth et al. (2016) saw seasonal correlations in TSS loads but not metal loads and, when incorporated into two artificial neural network (ANN) models, the model that directly predicted heavy metal loads performed better than the model that used TSS as a surrogate.

Three studies in 2016 focused on the potential human and ecological risk of heavy metal and PAH-polluted stormwater runoff from roadways (Chen et al., 2016; Liu, Liu, et al., 2016; Ma et al., 2016). To investigate the potential of reuse of stormwater runoff from roadways, Ma et al. (2016) explored the potential human health risk of heavy metals using the Environmental Protection Agency (EPA) Hazard index. Overall manganese (Mn), Cr and Pb posed the greatest risks although present at low concentrations. Using principal component analysis (PCA) the researchers also determined that health risk is significantly influenced by traffic volume and industrial land-use mirroring correlations found between heavy metals in roadway runoff and traffic volume and land-use. Liu, Liu, et al. (2016) also saw a correlation between PAHs with 4+ rings (PAHs which pose the greatest health risk) and traffic congestion. Chen et al. (2016) explored the toxicity of heavy metals, PAHs, and other contaminants present in roadway runoff through the use of the Nemerow pollution index (NPI) and biotoxicity tests on zebrafish and luminescent bacteria. Differences between NPI and experimental biotoxicity tests were observed; on average biotoxicity tests indicated runoff water quality was more toxic than predicted with NPI suggesting the EPA method cannot account for the mixed toxicity of runoff.

Not all 2016 publications were focused on heavy metals and impervious surface runoff. Huang, Chow et al. (2016) coupled high-performance size exclusion chromatography with ultraviolet light detection to better understand physiochemical properties of stormwater-transported dissolved organic matter in relation to rainfall and water quality characteristics. A number of other studies looked at multiparameter water quality conditions (Launay et al., 2016; Peng, Liu et al., 2016; Pennino et al., 2016; Ward and Winter, 2016). Peng, Liu et al. (2016) investigated chemical oxygen demand (COD), NH_3-N, Total P, and TSS in five different stormwater outfalls from three different drainage systems. Mean concentrations of the multiparameter study were greatest for the intercepting combined drainage system likely due to the combined nature of the system. Higher TSS loads were found in drainage from industrial areas while greater COD was found in residential areas. Moderate first flush behavior was seen depending on drainage system type. Pennino et al. (2016) looked at a similar group of parameters focused on carbon and nutrient fluxes including dissolved and total organic carbon (DOC, TOC), nitrate (NO_3^-) total nitrogen (TN), phosphate (PO_4^{3-}), total phosphorus (TP), iodide (I^-), and fluoride (F^-). Samples were collected over three years from urban streams, a restored stream, and a stream with upland stormwater management. The restored stream demonstrated small but statistically significant decreases in peak discharges and exported carbon, nitrogen, and phosphorus loads under low flow conditions while the urban streams did so at higher flow conditions. Isotopic analysis of NO_3^- indicated sewage as the primary source of NO_3^- in all streams tested.

Launay et al. (2016) conducted arguably the most exhaustive multiparameter analysis focusing on 69 micropollutants. Of these 69, 60 were detected; caffeine and acesulfame, an artificial sweetener, were consistently observed in high concentrations. The researchers observed two patterns in the behavior of micropollutants during rainfall: personal care products, artificial sweeteners and most industrial chemicals were diluted during rain events while biocides, PAHs, and two industrial chemicals increased in the combined sewer overflow (CSO) system during rainfall indicating contaminated surface runoff. Chinen et al. (2016) explored the use of a GIS volume-concentration method to identify relationships between pyrethroid (pesticide) concentrations in a creek of a small urban watershed and land-use, populations, and impervious cover. Overall, greater pesticide concentrations were found to correlate to greater population indicating residential surface runoff of pesticides. Ward and Winter (2016) argue that without educating individuals about how our actions on the land surface impact runoff water quality, individuals and industries remain blind to how their actions connect to the quality of water bodies in their community.

Bacterial indicators and stormwater temperature make up the remaining stormwater quality studies in 2016. The bacterial studies considered a variety of additional parameters in an effort to identify correlations between bacterial indicators of fecal contamination, which require incubation and time for growth, and parameters which can be quickly measured such as pH or temperature. Paule-Mercado et al. (2016) found correlations between fecal indicator bacteria and TSS, stormwater temperature, and turbidity. Galfi et al. (2016) also found positive correlations between the majority of parameters; water temperature, flow rate, and TP could explain 31-66% of variations in bacterial concentrations. However, no adequate surrogate for the bacterial indicators in either study was identified. Although temperature is not an adequate surrogate for bacterial indicators and identification of fecal contamination, first flush temperature effects due to stormwater runoff were observed over sites in Australia with an average 2-3°C temperature increase (Hathaway et al., 2016). Runoff temperatures from larger catchments were lower and less variable.

Common Themes and Future Work. The work summarized above represents a snap shot of the 2016 studies related to general stormwater quantity and quality. A noticeable increase in publications devoted to modeling of stormwater quantity and quality was evident, suggesting a shift in research toward the creation of predictive models. Land-use and climate change, when considered in concert, are expected to have compounding impacts on our stormwater runoff flows and water quality complicating the modeling process. Significant advances were made in the modeling of stormwater quantity and quality, but difficulties remain particularly in modeling stormwater quality and the build-up / wash-off processes responsible for the collection and release of stormwater pollutants.

Erosion and Sediment Control

Managing sediment from construction sites is an important aspect of overall stormwater control and treatment from urban areas. In 2016, 11 studies were identified that addressed wet-weather sediment and erosion control from construction sites.

Erosion Control. Three studies addressed erosion control, which serves as the first line of defense in managing runoff quality from construction sites. While chemical measures such as polyacrylamide (PAM) are known to suppress erosion, persistence in the environment has raised some concerns. Sadhegi et al. (2016) measured concentrations of PAM and unreacted residual acrylamide in runoff and sediment samples collected from plots with varying PAM application rates. An application rate of 2 g/m^2 PAM was identified as the optimal rate for minimizing both on-site soil erosion and offsite migration of PAM. Prosdocimi et al. (2016) reviewed the effectiveness of vegetative mulches for reducing runoff volume and sediment loads as well various methods and spatial scales of measurement. In another study of biologically-based erosion control materials, jute and coir textiles were found to reduce soil erosion rates over 90% on steep slopes under both lab and field conditions (Kalibova et al., 2016).

Sediment Control. Silt fences, ditch checks, and sediment basins were among the sediment control practices considered by studies published in 2016. Critical to assessing the effectiveness of such practices are well-defined testing methods and performance metrics. In line with this need, Donald et al. (2016) proposed the ratio of water depth to specific energy (which reflects the capacity of a ditch check to slow flow velocities) as a standardized metric for assessing ditch check performance to better enable cross-study performance comparisons across different flow conditions and channel geometries. A standardized testing method intended to produce repeatable performance tests in field-scale sediment basins was also proposed and applied to demonstrate the effectiveness of sump placement in a sediment basin forebay (Perez et al., 2016). Three additional studies presented design tools to further improve the design of sediment control practices. A set of procedures was developed to assist practitioners in determining design flow rates and volumes upon which to base selection and design of sediment control practices (Perez et al., 2016a). As demonstration, this method was applied to develop a set of design equations for the state of Alabama. Another design tool, SEDspread, was developed in a spreadsheet format to facilitate sizing and visualizing sediment basins and their associated components (Perez et al., 2016b). Based on lab-scale experiments in which setting velocities of fine textures soils were doubled though addition of PAM, Kang et al. (2016) concluded that sediment basin design could be reduced up to four times if such chemically-assisted flocculation with PAM was applied at the field scale. Finally, a field-scale experiment by Jang et al (2016) demonstrated the potential for silt fences and berms to reduce both sediment and nutrient export from agricultural fields, which, like construction sites, are subject to periods of bare soil, with reductions in

TP, COD and TN of 20%, 30%, and 40%, respectively, in edge-of-field runoff samples.

Inspection and Modeling. Two studies presented conceptual models for overall construction site runoff management. Belayutham et al. (2016) developed a framework based on literature review and semistructured interviews with industry professionals to improve integration of construction site stormwater management with the construction planning process. They identified scheduling as a key component of construction planning within which erosion and sediment control and post-construction stormwater management efforts can be effectively integrated. To assist with design decisions for construction site erosion and sediment control when expertise and/or data are limiting, Razak et al. (2016) coupled knowledge solicited from experts in sediment and erosion control with multi-criteria analysis to identify optimal combinations of practices to meet water quality targets. This model was applied to a case study in Malaysia, a country characterized by intense rainfall events, in which model-produced practice recommendations compared favorably with those from an experienced engineer.

Common Themes and Future Work. Despite relatively widespread efforts to reduce erosion and sediment delivery from construction sites, failure of control structures due to larger than expected stormwater volumes and energy is not uncommon. The models and design tools presented in several studies published in 2016 aimed to address this problem. While case studies were presented to demonstrate the application of these tools, study authors call for additional testing and validation. In addition to the need for further experimental research, the need to better quantify the economic costs of various sediment and erosion control practices was also highlighted. Such information is needed to conduct cost-benefit analyses for inclusion in construction site erosion and sediment control optimization efforts.

Constructed Stormwater Ponds

Construction of stormwater ponds for the collection and treatment of runoff are a standard practice around the world. Stormwater ponds are expected to reduce contaminant concentrations and attenuate rainfall events in a manner that is aesthetically and ecologically supportive. In 2016, 19 publications focused on the water quality, treatment efficiency, management and optimization of existing stormwater ponds.

Water Quality. Nutrient loads, particularly dissolved nitrogen (N) and phosphorus (P), are a common concern for the efficiency of stormwater ponds. Elevated levels of dissolved N or P in stormwater pond effluent can lead to eutrophication of waterbodies downstream. Duan, Newcomer-Johnson et al. (2016) showed that total dissolved phosphorus (TDP) concentrations in two stormwater ponds in Maryland USA were inversely related to dissolved oxygen (DO) concentrations. In addition, the stormwater ponds acted as a sink for P during high flow conditions, but became a source of P under low flow conditions when anoxic conditions may have allowed for the release of previously unavailable P. The bioavailability of dissolved organic nitrogen (DON) was also shown to increase between inlet and outlet stormwater pond conditions potentially accelerating eutrophication downstream (Lusk and Toor, 2016). In an effort to identify which ponds may, under current conditions, result in eutrophication downstream Tahsin and Chang (2016) developed a multivariate trophic state index (MTSI) which utilizes fuzzy synthetic evaluation to aid in decision making. The MTSI uses the current conditions of TP, TN, and secchi disk depth to determine eutrophication potential along with the TN/TP ratio to identify nutrient limiting conditions. All six of the stormwater ponds they assessed exhibited high eutrophication potential in the Fall and most were N-limited, or N-P co-limited.

Wet stormwater ponds can also act as a habitat for local flora and fauna, a benefit recognized by residents in adjacent residential areas (Monaghan et al., 2016). However, the presence of heavy metals in runoff can result in accumulation of metals in these retention structures and potentially the flora which populate them. Common metals in stormwater ponds include Cd, Cr, Cu, nickel (Ni), Pb, and Zn. In a variety of sedimentation structures in Sweden, 45-96% of Cd, 69-86% of Cu, 69-94% of Zn and 45-71% of Pb were found to be present in mobile forms which represent a greater potential for ecological harm (Karlsson et al., 2016). Two studies were published in 2016 that looked at bioaccumulation in fauna and sediments (Søberg et al., 2016; Stephansen et al., 2016). Søberg et al. (2016) collected heavy metal data from native fauna, caged mussels, and sediments in two wet retention ponds and a reference lake in Denmark. The fauna in the wet ponds had greater bioaccumulation of heavy metals, but only for bioaccumulated Cu were differences between fauna in the wet retention ponds and the reference lake statistically significant. In addition, no trends were identified in the bioaccumulation of heavy metals in the mussels after more than six months of runoff exposure in the pond, indicating that the presence of heavy metals did not hamper growth of the mussels. Stephansen et al. (2016) had similar difficulty in identifying statistically significant trends in the bioaccumulation of heavy metals or biodiversity of invertebrates. Although PCA showed bioaccumulation of metals in invertebrates from the 9 sampled ponds was different than those collected from the 11 shallow reference lakes, follow-up with detrended correspondence analysis (DCA) and TWINSPAN showed invertebrate populations in the pond could not be distinguished from those in the lake. Therefore, no statistically significant increase in risk to the fauna from heavy metals in retention ponds was identified in the 2016 literature.

As discussed in the stormwater quality subsection of this review, runoff carries with it a diverse range of contaminants. Other contaminants investigated this year include road salt, odors due to sulfide production, and pathogenic risk. She et al. (2016) investigated chloride concentrations in stormwater ponds from road salt and the potential impact on freeze-thaw behavior of the pond. Though chloride concentrations were evident, freezing point depression was minimal (yearly averages from 2 years of 0.072°C and 0.197°C) and did not result in statistically different freeze-thaw behavior. Sulfide and sulfate concentrations in two stormwater ponds were studied in an effort to understand and mitigate odors from the ponds (Ku et al., 2016). Ku et al. (2016) found that the addition of NO_3^- could inhibit sulfide production through the addition of a second terminal electron donor. As for pathogenic risks, Petterson et al. (2016) used quantitative microbial risk assessment (QMRA) to ascertain the human health risk from fecal pathogens in three stormwater retention structures also designed for stormwater harvesting. Pathogen removal was dependent on which microbial surrogate was chosen (*Escherichia coli*, somatic coliphages or *Clostridium perfringens*), the specific site, and the precipitation event. Though waterfowl also present a risk, the greatest risk of fecal pathogens was associated with potential contamination from older, poorly maintained sewer systems.

Comparing the concentrations of a particular contaminant or a class of contaminants as it enters and leaves stormwater ponds may be used to determine overall remediation efficiency. However, two issues exist with this approach: (1) observed differences in the concentration of the influent versus effluent are not always statistically significant, and (2) concentration is dependent on both mass of the contaminant and volume of the pond. To address the first issue, Brink and Kamish (2016a) suggest the use of a classification scheme to describe efficiency of the pond within the constraints of statistical and non-statistical relevance: generally unresponsive efficiency, significantly positive efficiency, significantly negative efficiency, not significantly positive efficiency, and not significant negative efficiency. Brink and Kamish (2016b) also suggest the use of mass not concentration as an indicator of pond efficiency supporting their argument with examples of opposing behavior; for example, where tracking mass in and out of the pond indicates the pond acts as a contaminant source while comparison of the concentration in and out of the pond demonstrates a reduction in contaminant concentration. The efficiency of stormwater ponds was also studied with respect to potential changes in contaminant loading due to climate change. Sharma et al. (2016) combined climate predictions with a catchment submodel of non-linear reservoir routing and a stormwater treatment unit submodel for micropollutants (STUMP) to create a dynamic stormwater runoff quality and treatment model to investigate the impact of climate change on a 95-ha catchment in Denmark. The researchers found no observable difference in dissolved Cu between current conditions and climate projects and found that although influent loads of TSS and Cu were greater in the climate change scenario (12% and 6%) the overall mass removal rate for Cu was similar (33.9% versus 32.5%). Climate change predictions represent future conditions; interestingly Sønderup et al. (2016) found that when comparing P, N, and Fe removal efficiency of stormwater ponds, the ponds which were greater than 10 years old demonstrated no retention capabilities for particulate or dissolved constituents. This suggests that regular maintenance of ponds is critical and that decreases in performance should be considered when modeling future behavior.

Design and Management for Optimization. Pond geometry is one parameter that can potentially be controlled and optimized to improve performance. Pond length, width, depth and surface area-to-perimeter ratio were shown to be correlated to water quality in 50 stormwater management ponds and 10 associated forebays (Chiandet and Xenopoulos, 2016). In addition, pond length-to-width ratio and outlet depth were identified as key factors in controlling pond temperature using gene expression programming and ANN models (Sabouri et al., 2016). Another design factor that can impact stormwater pond performance is the orientation of the pond versus the prevailing winds. Andradottir et al. (2016) measured wind and water currents in a 0.3-ha, 2-m deep stormwater pond and observed not only net clockwise lateral circulation, but also short-circuiting of flow paths within the pond. To mitigate this effect, underground stormwater retention ponds could be used; however, Drake et al. (2016) did not observe differences in water quality treatment, outlet temperatures, or stratification of temperature and dissolved solids between underground and traditional stormwater ponds. As a more integrated solution, Andradottir et al. (2016) suggest installation of wind breaks around the stormwater pond to shelter the ponds from wind-induced mixing and improve pond retention times. The performance of stormwater ponds can also be improved through the use of real time control (RTC) strategies implemented on the outlet of the pond (Gaborit et al., 2016). Essentially, RTC changes the outlet state (open/closed) based on precipitation and water residence time. For example, if a storm is forecast, the outlet is closed to ensure first flush contaminants are retained in the pond. This water is then held for a set residence time, in this case four days, unless potential flood conditions develop and then the outlet is opened. Gaborit et al. (2016) found RTC resulted in better TSS retention, fewer hydraulic shocks, and no flooding when compared to the commonly used static outlet configuration. Overall RTC represents a promising method for optimizing stormwater pond performance with potential to transition design toward smaller more efficient RTC ponds.

Common Themes and Future Work. Optimization of the pond shape, integrated landscape design, and active management of outlet flow rates ultimately show promise for improving overall stormwater quality. However, the literature from 2016 clearly emphasizes the importance of rigorous statistical methods and careful consideration of data quality and uncertainty. In addition, evidence of decreasing stormwater pond efficiency with age highlights the importance of regular maintenance of current stormwater ponds and suggests models of future conditions should, at a minimum, consider the impact of decreased efficiency on model predictions.

Constructed Stormwater Wetlands

Constructed stormwater wetlands (CSWs) are a type of stormwater treatment practice incorporating open water areas with shallow and temporarily inundated regions within which emergent macrophytes and other obligate/facultative wetland plants are supported. While CSWs are known to provide a variety of ecosystem services, the majority of the 19 CSW studies published in 2016 focused at least partially on their ability to sequester nutrients and metals across various temporal scales, as well as opportunities to better represent pollutant sequestration processes in models and enhance these processes through design optimization.

Field, Laboratory and Modeling Performance Studies. Experimental studies at the lab and field scales continue to demonstrate the potential to sequester nutrients and other stormwater pollutants in CSWs. For example, Merriman et al. (2016) tracked changes in pollutant removal over the first two years of operation of a CSW and found high retention rates of TSS and NO_3^- immediately after CSW construction, while the highest rates of phosphorus, total ammoniacal nitrogen and organic nitrogen retention were observed after the first growing season. Water quality improvements by a constructed floodplain wetland were also demonstrated by Ludwig et al. (2016), who, through a series of experimental flood events reported nutrient and sediment removal rates by a 0.2-ha constructed floodplain wetland on par with other CSWs. Investigation of heavy metal sequestration within a CSW was found to be greatest in storms greater than 15 mm, in which a higher proportion of metals were bound in particulate form, relative to smaller storms in which metals tended to be transported in dissolved form (Maniquiz-Redillas and Kim, 2016). Insights to within-wetland conditions and processes driving observed field-scale performance were provided by several other studies. Wetland soil characteristics (e.g., texture, pore size distribution) and relative elevation were significantly correlated with denitrification hot spots, within which a substantial portion of NO_3^- - delivered via stormwater and atmospheric deposition can be removed (Palta et al., 2016). Adyel et al. (2016) demonstrated the potential to use DO fluxes as a predictor of nutrient transformation and attenuation within surface and subsurface flow CSWs. In addition to soil characteristics and diurnal oxygen fluctuations, the presence of other stormwater pollutants may also influence nitrogen cycling in CSWs. For example, denitrification rates in soil cores collected from natural and roadside stormwater wetlands were found to decline under increasing chloride additions (Lancaster et al., 2016). However, the response was less marked in roadside stormwater wetlands, perhaps due to differences in denitrifying community structure, which was also measured as part of this study and which the authors suspect reflected adaptation to chronic chloride exposure within the roadside wetlands. Finally, while vegetation is credited with creating the conditions under which various pollutant removal mechanisms and other wetland functions occur (e.g., Merriman and Hunt, 2016), a critical review of heavy metal uptake by wetland plants indicated that this process is highly variable and not well understood (Vyzmal and Brezinova, 2016). Although the absolute quantity of heavy metals accumulated in aboveground plant tissues was low, a number of studies analyzed as part of this review indicated the relative fraction of the total metal load sequestered in plant shoots ranged as high as 70%, indicating the potential importance of this removal mechanism. As with ponds, several studies investigated potential tradeoffs between water quality benefits and aquatic biota health in CSWs. Despite bioaccumulation of heavy metals in benthic macroinvertebrates, evidence is lacking to suggest that metals are biomagnified further up the food web (Mackintosh et al., 2016b) or have harmful effects on developing frogs (Scheffers and Paskowski, 2016). Still, bioaccumulation of metals within benthic macroinvertebrates may suppress ecosystem functions mediated by these organisms. To examine this potential, Mackintosh et al. (2016a) examined organic matter decomposition rates in a set of CSWs and found that, while the contribution of macroinvertebrate shredders to decomposition processes was indeed negligible, overall decomposition rates were higher than observed in a set of natural wetlands. The authors concluded that other environmental variables (e.g., nutrient enrichment) likely bear stronger influence on decomposition rates than suppression by heavy metals.

Work to improve model representation of CSW hydrologic and pollutant removal processes also continued in 2016. A multiobjective generalized sensitivity analysis algorithm was used to identify sensitive parameters and successfully simulate hydraulic and hydrologic performance of a CSW within SWMM (Knighton et al., 2016). In a review of mathematical models developed to simulate phosphorus dynamics in constructed wetlands, Kadlec (2016) recommended that future models strive to improve representation of processes such as flocculation and P cycling within soils, sediments and vegetation. These recommendations were reflected in the work of Marois and Mitsch (2016), who demonstrated the importance of including plant community growth dynamics to accurately predict outlet P concentrations and speciation from constructed wetlands using the STELLA model.

Longer Term Performance. While hydrologic regulation and other ecosystem services provided by CSWs may develop in as little as two years (Merriman et al., 2016), data documenting long-term development and provision of these services are sparse. At least five studies published in 2016 contributed to this knowledge gap by examining water quality performance of CSWs ranging from 4 to 20 years in age (Adyel et al., 2016; Al-Rubaei et al., 2016; Corstanje et al., 2016; Kadlec, 2016; Xu et al., 2016). Each of these studies assessed P retention, which, despite the potential for P saturation and release from anaerobic wetland sediments over time, was found to continue with concentration reductions of 60% to 77%. Both Al-Rubaei et al. (2016) and Kadlec (2016) reported a plateau in outlet concentrations at an apparent "irreducible concentration" of 4 to 30 μg P/L for CSWs ranging up to 20 years in age. Field monitoring data from of a set of mature wetlands in Florida suggested surface water P concentrations are strongly coupled to nutrient concentrations within the wetland soils and floc (Corstanje et al., 2016). In addition to P, Al-Rubaei et al. (2016) examined long-term sequestration of other stormwater constituents by a mature CSW, and found that retention rates of Cu, TSS and TN increased significantly by 22 to 40% over 19 years of CSW operation. In another demonstration of long-term performance, Natarajan and Davis (2016b) documented similar water quality performance by a former infiltration basin that "transitioned" to a wetland over a 10-year period. Given potential for enhanced water treatment, Natarajan and Davis (2016a) developed a rapid assessment protocol to assess functional benefits of such systems that would otherwise be deemed as "failed."

Design Optimization and Innovations. CSW design optimization studies published in 2016 considered the effect of hydraulic design, in terms of the water quality volume (Niu, Park, et al., 2016) as well as amendments to enhance P sorption. With respect to the latter, aluminum-containing water treatment residuals exhibited potential for high sorption capacities (590-850 mg/kg) in batch experiments; however, flow-through experiments yielded removal rates of only 6-9 mg/kg (Vacca et al., 2016). Therefore, it is essential that CSW optimization efforts consider both sediment chemistry and hydraulic contact time with sediments. Adyel et al. (2016) presented a field-scale study of an innovative CSW system in which both sediment chemistry and system flow paths were manipulated through alternating surface and subsurface flow compartments, the latter of which was amended with laterite-based sediments to enhance P sorption. Indeed, field-scale retention of soluble and particulate P forms was about 60% over 7 years of monitoring this system. At the system scale, Dai et al. (2016) presented a GIS-based inexact optimization method (fuzzy-stochastic two-stage programming) to enable optimal placement of CSWs across a watershed in which stormwater pollutant load treatment is maximized while minimizing economic cost. Such models can facilitate decisions regarding placement CSWs and other stormwater treatment practices despite performance uncertainties.

Floating Treatment Wetlands. Four studies investigated the use of floating treatment wetlands (FTWs), a hybrid wetland-pond technology in which open water areas of stormwater ponds are retrofitted with mats supporting emergent macrophytes, to improve nutrient sequestration by stormwater pond systems. At the pond-scale, Hartshorn, Marimon, Xuan, Chang, and Wanielista (2016) reported reductions in effluent TN concentrations across three stormwater ponds following installation of FTWs for samples collected during storm events. In a companion study, Hartshorn, Marimon, Xuan, Cormier et al. (2016) examined correlations among microcystin abundance in stormwater ponds, nutrient concentrations, and the influence of FTWs. Observations in this preliminary study indicated that introduction of FTW's to the pond environment reversed trends between microcystin presence and nutrient concentrations; however, a limited sample size and influence of other unquantified site-specific factors limit the generalizability of these results. Efforts to better understand the mechanisms driving nutrient reductions by FTWs have included mesocosm studies to measure differences in nutrient uptake among plant species (Ge et al., 2016) and partitioning of sequestered nutrients among plant biomass and sedimented materials within the mat and root matrix (McAndrew et al., 2016). These studies both point to the importance of sedimentation as a removal mechanism while nutrient storage in plant biomass represents a relatively small proportion (5% to 34%) of total sequestration.

Common Themes and Future Work. CSWs are resilient systems, demonstrating continued capacity to provide pollutant removal and other ecosystem services over decadal time scales when properly designed and maintained. The adaptive capacity of the soil microbe community is a component of the resilience observed in CSWs. Additional understanding of the key mechanisms underlying successful pollutant retention within CSWs is needed to better understand opportunities for design optimization through, for example, intentional design of denitrification or phosphorus sorption “hot spots.” These optimization opportunities need to be understood at various scales in order to provide guidance for practical implementation at the field scale.

Bioretention

A bioretention cell, sometimes referred to as a rain garden, bioswale, infiltration swale, tree box filter, or a stormwater filter, is a shallow depression, often planted, that is designed to retain or detain stormwater before it is infiltrated or discharged downstream. Once again, bioretention for stormwater control and treatment was an active area of research in 2016, with at least 49 articles published during the year. In addition to the numerous research articles from 2016, Peng, Cao et al. (2016) published a comprehensive review on microbial removal by bioretention cells.

Field, Laboratory, and Modeling Performance Studies. Studies for characterization and optimization of bioretention were completed in 2016 for field applications, in the laboratory, and through modeling. While most field studies investigated water quality improvements, two studies focused solely on water quantity results including volume and peak reduction (Tang et al., 2016; Winston, Dorsey, and Hunt, 2016). Winston, Dorsey and Hunt (2016) monitored the water budget of three bioretention cells in tight soils in Ohio, where they found that the exfiltration rates were generally greater than the design values because of installed internal water storage zones. For 1-year rainfall intensities at these sites, the peak flow was reduced 24% to 96%, with the best performance occurring when the peak rainfall occurred before the centroid of the rainfall volume. Three studies at the field scale demonstrate the removal potential of bioretention cells for pollutants such as TSS, COD, BOD, total hydrocarbons (THC), TP, nitrogen species, Cu, trace elements, and PAHs (LaBarre et al., 2016; Leroy et al., 2016; Manka et al., 2016). An area of growing interest that produced three more field-scale papers in 2016 is in the area of long-term performance of bioretention cells (Horstmeyer et al., 2016; Johnson and Hunt, 2016; Nichols and Lucke, 2016). Horstmeyer et al. (2016) collected 262 surface soil samples from 35 roadside infiltration swales and identified numerous factors that contribute to heavy metal accumulation in these soils. Additionally, Johnson and Hunt (2016) spatially sampled an 11-year-old bioretention cell in Charlotte, North Carolina, and determined that with proper maintenance of the forebay, the effective life of the cell should exceed the life of the developments they treat. Finally, Nichols and Lucke (2016) discussed a series of experiments on 10-year-old cells in Australia. These researchers found that the cells exported pollutants in tests where no pollutants were added, and that TPd loads were decreased for all tests. Despite being close to roadways and contrary to expectations, only minimal amounts of hydrocarbons and heavy metals were found within the media of these cells. Finally, Dietz (2016) published a technical note that confirmed previous studies indicating that an internal water storage zone will improve nitrogen removal capability of bioretention cells.

Laboratory and mesocosm studies can be an efficient method for testing the performance of bioretention cell media in a robust manner. Gülbaz and Kazezyilmanz-Alhan (2016) tested the impact of drainage area soil characteristics and rainfall intensity and duration on hydrologic variables at the bioretention outflow. Several studies investigated the removal capabilities of typical bioretention cells for various pollutants, including nitrogen (Guo et al., 2016; Subramaniam et al., 2016), Cd (Wang, Zhang, Yang and Huang, 2016), and bacteria (Chandrasena et al., 2016). Two studies (Huber, Badenberg, et al., 2016; Zhang, Valognes et al., 2016) have utilized laboratory-scale studies to develop testing methodology for validating the effectiveness of bioretention media. The paper by Huber, Welker, Dierschke, et al. (2016) described a test for pre-loading media with Cu and Zn equivalent to nearly the expected life (n-1 years) of the cell, and then testing for removal efficiency of these metals. Zhang, Valognes, et al. (2016) described a development and testing in-situ column study that was completed in an intact bioretention cell for determining the performance of existing practices. This test was further developed from a modeling standpoint in Zhang, Randelovic, et al. (2016).

Modeling is another tool that can be utilized to investigate the performance of bioretention cells, especially over larger scales. Jennings (2016) compared the hydraulic performance of similar rain gardens in 35 locations across the United States. Modeling and life cycle analysis was also used by Wang, Zhang, Adhityan et al. (2016) to investigate the impacts of climate change and urbanization. This study determined that bioretention was more sensitive to urbanization than climate change for the scenarios investigated. For individual systems, three studies developed models for simulating bioretention cell or infiltration gallery performance (Jennings and Baker, 2016; Randelovic et al., 2016; and Zhang, Randelovic et al., 2016).

Enhanced Media. One of the most active areas of research for bioretention is developing enhanced bioretention media to improve water quality performance, with at least 13 papers written in 2016 that used both organic and inorganic additives. Similar to research that was published in 2015, Chahal et al. (2016) demonstrated NO_3^-, P, and dissolved organic matter leaching into effluent of a bioretention cell that was amended with compost. For Cu, the compost-amended media was a source during the first three to five storms, but then the media became a sink. Additionally, Brown et al. (2016) indicated that the phosphorus saturation index (PSI) could be used as a predictive tool for estimating treatment capacity and that compost source was not a good indicator of the ability of the compost to filter contaminants. Logsdon and Sauer (2016b) demonstrated leaching from compost-amended media and recommended that only small amounts of low-nutrient compost should be incorporated into bioretention media. Another common organic bioretention media amendment that was investigated in 2016 was biochar. Miles et al. (2016) published a comprehensive overview of aqueous contaminant sequestration by biochar in stormwater treatment systems. Additionally, Tian et al. (2016) demonstrated ammonium sorption for biochars from hardwood and poultry litter, and

Komkiene and Baltrenaite (2016) demonstrated the removal capacity of heavy metals (Cd, Cu, Pb, and Zn) of biochar made from Scots pine and Silver birch. Wood and wastewater sludge biochars were also shown to be effective for removing the veterinary antibiotic sulfamethoxazole by Shimabuku et al. (2016). Two studies investigated the use of granular activated carbon in bioretention media, showing removal potential of dissolved organic matter, turbidity, heavy metals (Sountharajah et al., 2016), and NO_3^- (Erickson et al., 2016) using this bioretention media amendment. A study by Schifman et al. (2016) investigated the use of an organic amendment (red cedar wood chips) coated with the antimicrobial agent 3-(trihydroxysilyl)propyldimethlyoct-adecyl ammonium chloride in a tree filter and found that the amended media worked better than traditional media for TSS, PAHs, NO_3^-, and PO_4^{3-}. However, *E. coli* removal was not significantly different between the two systems, perhaps as result of limited contact time with the amended media.

In addition to the organic amendments, a number of inorganic bioretention media amendments were investigated in 2016, including aluminum-based water treatment residuals, montmorillonite treated with aluminum sulfate, aluminum-oxide coated sand, granular activated alumina, granular ferric hydroxide, calcium carbonate, granular activated lignite, copper zeolite, coal ash, scrap tire rubber, reclaimed asphalt pavement, recycled crushed brick, and iron slag (Deng et al., 2016; Huber, Hilbig et al., 2016; Johannsen et al., 2016; Li, Jiang et al., 2016; Li, McCarthy and Deletic, 2016; Yan et al., 2016). Johannsen et al. (2016) demonstrated increased removal efficiency of dissolved organic carbon when sand was coated with aluminum oxide. Dissolved phosphorus sequestration was enhanced by treating bioretention media amendments (here, aluminum-based water treatment residuals and montmorilllonite) with ammonium sulfate. (Yan et al., 2016). Li, Li, et al. (2016) showed that coal ash mixed with sand removed COD, TN, and TP. Li, Jiang, et al. (2016) found that blast furnace slag worked well for removal of P, N, and heavy metals in bioswales. Reclaimed asphalt pavement and recycled crushed brick also demonstrated potential as a bioretention amendment for removing TSS, TP, and TN (Rahman et al., 2016). Copper zeolite was shown to increase *E. coli* and Cu removal rates compared to sand-only bioretention media in a study by Li, McCarthy et al. (2016). Deng et al. (2016) found removal of Cu, Pb, and Zn by water treatment residuals while use of scrap tire rubber as a bioretention filtration media removed Cu and Pb but leached Zn. However, leaching of Zn was significantly reduced by combining scrap tire rubber with the water treatment residuals. When comparing batch study and column study results for six different amendments, Huber, Badenberg et al. (2016) found that column studies were a more realistic test than batch studies when determining removal efficiencies and service lives of amended media. Logsdon and Sauer (2016a) published the findings of laboratory studies demonstrating that iron filings were not suitable as soil amendments for engineering media because they caused cementation of the soils.

Two additional papers were published in 2016 in which the use of bioretention media that utilize both organic and inorganic media was investigated. Zhou et al. (2016) demonstrated impressive phosphorus and nitrogen removal efficiencies of by adding iron-rich soil, plant detritus, and eutrophic lake sediment. Improved removal of metals (Al, Fe, Cu, Cr, Ni, Zn, Cd, and Pb) was reported in biofilters that used iron-rich red soil, fine sand, perlite, coco-peat, and Sargassum biomass (a type of seaweed; Vijayaraghavan et al., 2016).

Vegetation and other biota. At least four studies in 2016 investigated the impact of plant type on water quality improvement performance of infiltration-based LID practices. Li, Li et al. (2016) discovered that plant type did not make a significant difference in nutrient removal in bioswales in 2-month-long experiments, while Nocco et al. (2016) and Turk et al. (2016) found that vegetation impacted the nutrient budget in bioretention cells. In addition, Rycewicz-Borecki et al. (2016) found that various macrophyte species exhibited varying levels of metal bioaccumulation in simulated bioretention systems. Leroy et al. (2016) found that vegetated swales planted with deep-rooted macrophytes had better removal of TSS, COD, nutrients, and metals than swales planted with turfgrass. In one of the few studies to examine the functional role of soil macroinvertebrates in bioretention systems, Mehring et al. (2016) found that over 400% of the upper 5 cm of soil was ingested annually by earthworms residing in a bioretention system, suggesting that the role of these organisms in N cycling may be substantial and warrants additional research.

Environmental Impact and Other Benefits. Going beyond simple performance assessment and investigating ecosystem and societal impacts of LID practices is an essential next step towards widespread implementation. McIntyre et al. (2016) found that bioretention removes PAHs and protects against the cardiotoxic impacts of these compounds to zebrafish. In addition, Dagenais et al. (2016) completed a pilot study to investigate the impact of bioretention cell location within a watershed on optimization of secondary benefits, including reducing climate change vulnerability while improving aesthetics, air quality, biodiversity, and many societal benefits.

Common Themes and Future Work. As demonstrated by the body of bioretention research published in 2016, the potential to optimize bioretention cell function to meet specific pollutants and/or hydrologic targets is promising. While efforts to understand physicochemical aspects of bioretention systems remains a primary research focus, there is a growing effort to understand biologically-mediated processes in bioretention systems; future research and optimization efforts should aim to integrate understanding of biological (e.g., the influence of vegetation and other resident biota on bioretention function) and physical-chemical mechanisms driving bioretention performance. Furthermore, it is also expected that co-benefits provided by bioretention systems will continue to be quantified and incorporated in bioretention design and optimization at various scales.

Permeable Pavement

As supported by the findings of a state-of-the-art review (Chandrappa and Biligiri, 2016), permeable pavement systems – which include permeable concrete, asphalt, and block pavers – continue to rise in popularity as a LID practice due to their ability to serve as a pavement system and stormwater control system. Accordingly, over 20 papers were published in 2016 to better understand the interplay of hydraulic properties, pollutant removal mechanisms, system design and maintenance.

Hydraulics and Related Properties. The majority of studies related to permeable pavement hydraulic properties in 2016 were conducted at the field scale. Alyaseri and Zhou (2016) monitored runoff volume reduction by permeable pavement systems installed in alleyways of St. Louis, MO as part of the city's CSO reduction program. From the pre- to post-installation monitoring period, significant reductions in the rainfall-to-runoff ratio were observed for permeable concrete and paver systems (36% and 46%, respectively), but not for permeable asphalt, likely as result of the steeper slopes on which this pavement type was installed. Permeable pavement infiltration rates were the focus of several field studies, and were shown to depend upon factors such as degree of tire compaction (Cipolla et al., 2016; Kumar et al., 2016), winter sand applications (Huang et al., 2016b) and time (Kumar et al., 2016; Winston, Al-Rubaei, Blecken, Vicklander, and Hunt, 2016). In most cases, however, infiltration rates under clogged conditions remained greater than design rainfall intensities. While the majority of these studies followed ASTM infiltration standards for infiltration measurements, Winston, Al-Rubaei, Blecken, and Hunt (2016) demonstrated the utility of a modified infiltration test that correlates well with ASTM-based procedures but requires less time to apply and, arguably, better represents ponding conditions under which permeable pavement systems infiltrate. Winston, Al-Rubaei, Blecken, Vicklander, and Hunt (2016) conducted a study to better understand which practices were most effective for maintaining or restoring infiltration rates in permeable pavement systems and found that, out of eight different maintenance measures tested, nearly all increased the frequency with which permeable pavement systems were able to completely infiltrate the design storm intensity from direct rainfall and, when applicable, adjacent runon. In the case of severely clogged permeable asphalt, milling and reinstallation was the only maintenance measure to restore infiltration rates. Regardless of the maintenance practices selected, the authors suggest increased frequency is necessary with pavement age. Under non-clogging laboratory conditions, the influence of different permeable surfaces and aggregate base structures on hydraulic performance metrics (lag times, retained rainfalls, times to peak, and peak outflows) were examined (Rodriguez-Hernandez et al., 2016). While subbase materials had the greatest influence on hydraulic properties immediately following construction, the permeable surface type (here, interlocking concrete blocks and permeable asphalt), had greater influence on the hydraulic behavior through time due to surface infiltration characteristics.

Modeling. Efforts to enhance permeable pavement design and maintenance through improved prediction of hydraulic behavior continued in 2016.

Brunetti et al. (2016) validated the performance of the mechanistic model HYDRUS-1D to predict outflow hydrographs from permeable pavement systems. In accordance with experimental data presented by Rodriguez-Hernandez et al. (2016), sensitivity analysis of the model indicated the importance of the surface layer on hydraulic behavior. Furthermore, this study demonstrated the utility of a particle swarm optimization approach for model calibration and parameterization. HYDRUS-1D was also found to provide a good representation of infiltration and runoff dynamics for a concrete grid paver system in Brazil (Coutinho et al., 2016). Permeable pavement hydraulic and effluent TSS characteristics were successfully simulated with a numerical model coupling a modified Kozeny-Carman equation for 1-D vertical flow with a mathematical model of sedimentation (Huang, He, et al., 2016) based on experimental data collected by Huang et al. (2016b). ANNs were also shown to be an effective modeling approach for predicting both runoff volume capture (Radfar and Rockway, 2016a) and peak volumetric water content of the aggregate storage layer as a potential predictor of clogging (Radfar and Rockway, 2016b). As a secondary benefit of hydrologic regulation, evaporation from permeable pavement systems may contribute to microclimate regulation. Qin and Hiller (2016) tested this assertion by applying a 1-D numerical heat transfer model of permeable pavement surfaces following surface wetting. The model indicated that evaporative cooling is driven by water availability near the surface of the pavement system and that, after near-surface water storage is depleted (within a 24-hour period under the relatively hot and dry conditions to which this model was applied), permeable pavement surface temperatures may be equal to or greater than conventional pavements.

Water Quality. Permeable pavement systems are generally understood to improve water quality through filtration of suspended solids and other particulate-borne pollutants; water quality investigations of permeable pavement systems in 2016 generally supported this understanding. For example, Huang et al. (2016b) found TSS, TP and heavy metal removal was consistently high (> 80%) and did not vary significantly among season, permeable pavement type or hydraulic performance; however, TN removal declined with decreasing pavement temperature. In contrast, Antunes et al. (2016) observed an increase in nutrient concentrations in effluent from a permeable asphalt surface, a result that may indicate leaching of ammonia- and phosphorus-based polymers present in the asphalt. The effects of gravel bed thickness (Niu, Lv, et al., 2016) and gravel size (Huang et al., 2016a) on water quality performance were also examined at the lab scale, and were used to develop mathematical models to predict pollutant removal for a given pavement type and gravel bed composition (Huang et al., 2016a). In line with previous findings, these studies reported high particulate removal rates. However, for the first time in the literature, an increase in TSS load from permeable pavement outflow was documented (Winston, Davidson-Bennett, et al., 2016). Due to the seasonal timing of observed TSS pulses, the authors speculated wintertime deicing salt applications dispersed underlying clay soils, which, along with elevated cation concentrations (Al, Ca, Fe, Mg, Pb), migrated through the underdrain system. Such unintended water quality effects could be experienced in other systems in which sodium-based deicing salts are applied and underlying soils are comprised of 2:1 clay minerals. Besides de-icing practices, some permeable pavement systems are subject to application of herbicides such as glyphosate. When applied at typical concentrations, glyphosphate applications were found to impact beneficial bacterial communities residing within permeable pavement systems and to raise effluent turbidity (Mbuanaso et al., 2016). However, effluent conductivity and sodium adsorption ratio remained within agriculturally acceptable limits such runoff harvested from such systems could be used as an irrigation source.

Innovations. Innovative permeable pavement applications included incorporating recycled materials in permeable pavement mixtures and integrating with water harvesting. With respect to the former, Chang et al. (2016) found that electric arc furnace slag and alkali-activated slag cement could be incorporated in permeable concrete mixtures to achieve higher compressive strength (35 MPa compared to less than 21 MPa in most permeable concrete mixtures) while maintaining satisfactory water permeability rates (5 mm/s). Incineration bottom ash was also explored as a substitute for sandstone materials in permeable brick pavers (Wu et al., 2016). In this case, the compressive strength of the optimal mixture was greater than that of standard brick pavers, but the permeability coefficient was low (0.1 mm/s) relative to most design rainfall intensities. In a study of innovative material mixtures for the aggregate storage layer underlying permeable pavement systems, tracers were used to characterize the hydrodynamic behavior of recycled crushed concrete and organic matter mixtures (Bentarze et al., 2016). Increased capillarity and water retention by organic matter in these mixes was found to enhance runoff storage within the system. The potential to incorporate permeable pavement with broader integrated water management strategies in drought-prone areas was also modeled. In a case study of Florianopolis, Brazil, Antunes et al. (2016) demonstrated that converting 0.1% of the city's existing paved area to pervious pavements and providing 0.1 m^3 water storage per m^2 of permeable pavement area could offset 20% and 70% of residential and public sector water usage, respectively.

Common Themes and Future Work. These studies continue to confirm the contribution of permeable pavement systems to both stormwater peak and quality mitigation under most circumstances, provided proper maintenance practices are conducted. Future work is needed to better understand the influence of hydrologic loading, slope, and other design characteristics on hydrologic and water quality performance. Additional work is also needed to understand tradeoffs in compressive strength and pavement hydraulic properties to further advance application to higher volume roadways. Finally, future research should also continue to address potential microclimate and urban heat island-related benefits provided by permeable pavement systems under a range of climatic conditions and pavement designs.

Greenroofs

In 2016, there was a marked decrease in the number of publications related to the performance, modeling, and augmentation of greenroofs. However, there remains an impressive breadth of subject matters spanning full-scale greenroof hydrologic models to novel substrate amendments. Note that studies pertaining to the modeling of catchment scale implementation of greenroofs (Masseroni and Cislaghi., 2016; Schmitter et al., 2016) can be found in "Watershed-scale Assessment".

Field, Laboratory and Modeling Hydrologic Performance Studies. Field and laboratory studies dominated the 2016 publications with a focus on the impact of various greenroof and climate parameters. In an effort to remove the impact of climate variables on greenroof performance, Elliott et al. (2016) analyzed the hydrologic performance of one thick and one thin greenroof in New York City. The two roofs demonstrated different water retention due to structural difference such as media depth and vegetation. Both roofs demonstrated similar seasonal trends to those seen in the literature including increased water retention during warm months, especially following long ADP; these trends were more pronounced for the thin roof.

Increased retention following long ADP was also confirmed for varying thicknesses of a greenroof using a HYDRUS-1D model (Feitosa et al., 2016) assuming all other modeled parameters were identical. Selection of greenroof media generally depends on desired hydrologic and thermal properties. It is important to note that hydrologic and thermal performance is not a trade-off, with some materials outperforming their counterparts in both metrics (Jelinkova et al., 2016). However, predicting the hydraulic behavior of greenroof media is difficult even when given basic properties of aggregate, compost, and topsoil mixtures (Liu and Fassman-Beck, 2016).

Though several studies still look to ADP to predict stormwater retention, support for the use of antecedent soil moisture conditions (AMC) in predicting stormwater retention has increased. Sims et al. (2016) looked at three greenroofs across three different climate zones in Canada and found that, despite differences in precipitation patterns between the sites, AMC was the best predictor of stormwater retention. AMC is directly tied to climate conditions, media characteristics, plant type, and evapotranspiration (ET) rates of greenroofs. As such, additional study into proper parameterization of the Penman Monteith equation for estimation of ET rates is needed especially in climate regions where ET rates are high (Starry et al., 2016; Zaremba et al., 2016).

Incorporation of proper ET rates is extremely important for modeling greenroof performance following a single precipitation event whether using simple, physically-based mass conservation methods (Li and Babcock, 2016) or more advanced modeling via software such as HYDRUS-3D (Brunetti et al., 2016) and SWMM 5.1 (Cipolla et al., 2016). All three models include parameters to account for variability in soil moisture including daily accounting for soil moisture in the HYDRUS-3D model. Cipolla et al. (2016) demonstrated the use of a 6-month calibrated SWMM 5.1 model to simulate year long performance of a greenroof with only a 9% overestimate of discharge volume. The model success in 2016 suggests acceptable catchment-scale modeling of greenroof performance may be on the horizon.

Water Quality and Substrate Amendments. Water quality studies pertaining to greenroofs were less common in 2016. However, all studies demonstrated buffering ability of the greenroof systems and generally elevated nutrient concentrations in the effluent. Elevated P concentrations were found in effluent from a greenroof in Malaysia (Kok et al.,2016) as well as multiple greenroofs in New York City (Whittinghill et al., 2016). The P and potassium (K) concentrations in the runoff of a rooftop farm were above EPA guidelines suggesting improved nutrient management is needed for intensive greenroof systems (Whittinghill et al., 2016). Increased levels of N and DOC were also reported along with seasonal variations in nutrient concentration and greater nutrient loads during growing seasons (Carpenter et al., 2016).

The increase of nutrient loads from greenroofs has spurred investigations into novel substrate amendments for water quality improvement as well as general investigations into repurposed substrate materials. For example, biochar has been suggested as an amendment to improve water quality and increase water retention. Results of biochar studies have been mixed; initially the addition of biochar showed no improvement in water quality but after a year of use a decrease in nutrient loads was observed (Kuoppamäki and Lehvävirta, 2016). In a second experiment, different sources of biochar produced drastically different water quality results: one biochar source decreased runoff volumes and nutrient loads while a second biochar source resulted in an increase in nutrient loads (Kuoppamäki et al., 2016). Similarly, Liu and Coffman (2016) observed an increase in NO_3^- and hardness following the use of a new repurposed lightweight aggregate material made from dredged sediments from the Harbor of Cleveland in Lake Erie. Both studies suggest the importance of rigorous testing before new substrate amendments are added to greenroof systems.

Vegetation. There is little debate that the type of vegetation used for a greenroof impacts water retention and that seasonal growing patterns may result in seasonal variations in nutrient loads (Carpenter et al., 2016). However, many laboratory scale tests vary their planting methods, and field-based studies generally look at established greenroofs where plant choice is out of the researchers' control. Controlling plant species and growth media, Aloisio et al. (2016) conducted a microcosm experiment and observed differences in stormwater retention and nutrient (NO_3^- and TP) loads across varying plant types. However, this study considered single species microcosms and there is substantial evidence that biodiversity can improve system resilience. Increased biodiversity in greenroof plants was associated with increased biomass and nitrogen retention with no statistical difference in runoff or P loading, suggesting there are no negative impacts of increasing plant diversity when designing greenroofs (Johnson et al., 2016).

Common Themes and Future Work. Over the past year, the role of soil moisture has gained momentum as one of the best indicators for greenroof water retention. However, this means researchers must precisely define parameters which impact soil moisture and ET rates including drainage configurations, soil types and amendments, vegetation, and the regional climate. New models, whether physical or empirical, need to be designed to account for these complex interactions. Finally, as we design new greenroofs, site specific parameters are vital and any new substrate amendments need to be well vetted before use to avoid unintentional consequences such as increased nutrient loads.

Rainwater Harvesting

Rainwater harvesting is a practice that can reduce demand on local water supplies and attenuate stormwater runoff. The system must collect, treat, store, and distribute water to be an effective secondary water source. Harvesting must also be possible across varied land use types to be an effective stormwater management method (Ghaffarian Hoeini et al., 2016). The optimal design of a rainwater harvesting system requires consideration of local climate, runoff water quality, water demand, and cost.

Water Quality. As outlined in the stormwater quality section of this review, several contaminants of concern present in stormwater runoff may affect suitability of harvested rainwater for various uses. For example, the use of runoff from roadways or collected from permeable pavements may contain PAHs and herbicides which could present a significant health risk if consumed (Liu, Liu, et al., 2016; Mbanaso et al., 2016). Petterson et al. (2016) demonstrated lower water retention yields and microbial risks when stormwater treatment facilities doubled as rainwater harvesting systems. However, the utilization of ordinary or green stormwater infrastructure for rainwater harvesting is a common point of implementation. Rooftops are the most common retrofit for rainwater harvesting. However, rooftop runoff, like that from other land uses, may contain a range of anions and cations, suspended solids, and bacteria. Taffere et al. (2016) collected mean concentrations of a several ions and found highest anion concentrations of SO_4^{2-} and cation concentrations of Ca^{2+} and Mg^{2+}. Large spatial and temporal variation in the ions was attributed to activities from traffic and industrial areas. While Taffere et al. (2016) found the pH of the collected water to be alkaline, Ezemonye et al. (2016) found their collected water to be acidic. Samples were collected from asbestos, aluminum, and galvanized roofs and were characterized by Fe and bacteria levels above WHO guidelines at the start of the rainy season. Effluent water quality differences among the three types of roofs were not statistically significant, suggesting all three produce the same level of water quality for rainwater harvesting systems and would require treatment before consumption. Some researchers are looking into the use of greenroofs to collect, store, and potentially treat rooftop runoff. While greenroofs coupled with rainwater harvesting approaches can produce a sufficient quantity of water to meet household demands, the use of this water remains non-potable (Monteiro et al., 2016). Sultana et al. (2016) collected conductivity, DO and pH measurements from rainwater collected from a greenroof in Malaysia and compared these measurements to the Malaysian Department of Environment Interim National Water Quality Standards (INWQS) and Water Quality Index (WQI). Conductivity values remained within acceptable limits of Class 1 but DO and pH varied, occasionally falling into Class III conditions requiring considerable treatment before use.

Design Optimization. Rainwater harvesting has the potential to attenuate stormwater peak flows depending on precipitation, demand for harvested water, and size of the tank (Campisano and Modica, 2016). In humid regions, utilization of harvested water is not needed as frequently, and therefore collection systems may be close to capacity already before a storm occurs. Gee and Hunt (2016) investigated the use of passive and active rainwater releases in North Carolina, USA. In the passive scenario, water was slowly released between storms while the active scenario released water when future rainfall events were predicted. Both systems demonstrated significant reductions in runoff volume and peak flow with slightly higher reductions from the active release system. Although the results are promising, the two systems did not experience any extreme events and therefore performance under extreme conditions is unknown. Tavakol-Davani et al. (2016) demonstrated the potential benefit of rainwater harvesting on CSO events in Toledo, Ohio using the Coupled Model Intercomparison Project Phase 5 (CHIP5) and the SWMM rainfall-runoff model. In predicting the effects of climate change, the model showed an 18% increase in CSO frequency, 12% increase in the volume of CSO discharge, and 17% increase in the duration of CSO events, but the implementation of 0.76-m^3 cisterns throughout the city were shown to alleviate this increase.

Optimization of rainwater harvesting designs often falls back to cost. The work of Melville-Shreeve et al. (2016) introduced several rainwater harvesting configurations for houses in the United Kingdom based on balancing costs with benefits. The approach looks to minimize the capital costs of the design and operational energy consumption, maximize the water savings, and minimize stormwater flow from extreme events and CSO events based on reduction in water discharges to the sewers. Pelak and Porporato (2016) looked to optimize the volume of rainwater harvesting cisterns through identifying the optimal cistern size. The method focuses on costs associated with rainwater harvesting systems and incorporated the uncertainty of rainfall through the use of a stochastic water balance. Though not incorporated in this model, Pelak and Porporato (2016) suggest benefits from stormwater volume reductions could be included in the model through the use of a “stormwater fee” which would be based on the volume of stormwater sent to the municipal system; this practice is currently employed by some water treatment municipalities.

Economics and Ecosystem Services. Two papers in 2016 focused on the economics of rainwater harvesting cisterns in terms of city-wide implementation versus cistern design optimization (Dallman et al., 2016; Valdez at al., 2016). Both cities had a high population density but the approach, assumptions, and metrics varied. In California, Dallman et al. (2016) focused on the balance between costs for rainwater harvesting systems and the benefits of outdoor and indoor non-potable use. With all costs remaining the same, only small outdoor non-potable rainwater harvesting systems had a positive net benefit. However, projecting increasing costs of potable water, larger outdoor systems could produce a positive net benefit in the future. Indoor non-potable use systems remain expensive due to high capital installation costs. This study did not account for intangibles such as potential changes in property values or carbon emission savings. Valdez et al. (2016), who explored the cost benefits of rainwater harvesting in Mexico City, did account for carbon emissions by balancing cumulative energy demand, global warming potential, and net present value indicators in their analysis. The researchers evaluated 11 possible building types of varying use and height and found the most value in rainwater harvesting from high rise buildings that can utilize gravity-fed non-potable water supplies. However, the use of rainwater harvesting systems in small infrastructure such as individual homes showed little benefit.

Common Themes and Future Work. The potential of rainwater harvesting to reduce stormwater volume and supplement water supplies shows great promise. However, the quality of harvested rainwater remains problematic for potable use, and thus, methods for optimizing their design are constrained by the assumption that these will represent non-potable supplies. Missing from these scenarios is the human dimension: will citizens accept rainwater harvesting and maintain systems once they are in place? Gao et al. (2016) found that the answer to this question depends on the individual. Those who have positive opinions about the environment and possess greater knowledge of the practice are more likely to adopt it. Gardeners, for example, are the predominant adopters of rainwater collection systems. However, after inventorying rain barrels in two Indiana watersheds, 25-35% of rain barrel systems were no longer in operation. Like many green stormwater techniques, citizen buy-in is critical to continued operation and success of rainwater harvesting systems.

Watershed-scale Assessment

While negative impacts of urban development – specifically increased impervious surface cover and drainage density, on watershed hydrology, water quality and stream ecosystem health – have been observed, the capacity to mitigate these affects through distributed, infiltration-based stormwater treatment practices is not well understood. In 2016, over 20 studies sought to advance this understanding through field monitoring and/or modeling. These studies, and their implications to watershed-scale management, are reviewed in subsequent sections.

Field assessment. The scale of LID implementation in some watersheds has enabled quantification of LID's influence upon stream hydrology and water quality. For example, stream hydrology and nutrient fluxes were examined across a gradient of development and LID implementation in 25 watersheds ranging up to 34 km^2 in the US Mid-Atlantic (Pennino et al., 2016). In this analysis, watersheds in which LID practices intercepted runoff from over 5% of watershed impervious area had significantly lower stream flashiness metrics and longer flow duration. While not as strong statistically, declining nutrient loads were also associated with degree of LID implementation. In a similar study, Bell et al. (2016) assessed impacts of stormwater treatment practices (constructed ponds, wetlands and bioretention) upon stream hydrology in 16 watersheds, ranging from 2.5 to 33 km^2, in Charlotte, NC. Unlike Pennino et al. (2016), streamflow flashiness and water yield were not statistically correlated with stormwater management-based predictors, but, rather, with watershed imperviousness and tree cover. At the event-scale, streamflow dynamics were best predicted by total watershed imperviousness, while metrics incorporating the degree to which stormwater practices were implemented in the watershed did not have discernable effect. These results suggest the range in mitigated impervious area (1 to 89%) and/or the types of stormwater treatment and control practices implemented in this study were not sufficient to overcome the influence of remaining unmitigated impervious area on stream hydrologic response; however, there may be characteristics other than aggregate impervious area mitigation (e.g., spatial-based characteristics) that provide better predictors of stream hydrology. Effects in smaller watersheds may be more evident; Jarden et al. (2016) reported peak flow and volume reductions of 33% and 40%, respectively, following implementation of bioretention areas and rainwater harvesting in street-scale watersheds up to 0.12 km^2 with a before-after-control-impact (BACI) monitoring design in Cleveland, OH. The authors also highlighted complexities inherent in such field studies, as concomitant activities such as street curb and gutter installation masked LID effects on storm sewer discharge in one of the study watersheds. In addition to reducing stream flashiness when implemented at an adequate scale, stormwater treatment practices, particularly infiltration-based systems, may also increase stream baseflow (Bhaskar, Beesley, et al., 2016). While baseflow increases may provide benefit in some stream systems, such increases likely arise as a tradeoff in watershed ET (Bhaskar, Hogan, and Archfield, 2016), indicating potential limits to fully mimic predevelopment hydrology through focused infiltration within LID practices unless predevelopment vegetation cover is maintained.

Modeling Assessment and Optimization.

Watershed modeling studies published in 2016 assessed LID function across a range in watershed size (0.1 to 400 km^2), climate (semi-arid to tropical), and development patterns, thus providing insight to diverse contexts and scales across which LID strategies may influence watershed processes. With respect to watershed hydrology, two studies focused on watershed-scale impacts of rainwater harvesting. While reductions in peak flow (11-22%) and volume (7-18%) were predicted for a 1.5-km^2 watershed in Barranquilla, Columbia under storms ranging from 134 to 175 mm (Avila et al., 2016), these changes may not address ecologically-relevant watershed flow conditions (Aryal et al., 2016). In a case study of LID performance in a 0.1-km^2 watershed in Utah, USA, Feng et al. (2016) introduced the “water budget restoration coefficient” to characterize the capacity for LID to shift various components of the water balance (surface runoff, ET, percolation, soil moisture storage, and surface storage) toward predevelopment conditions as predicted by the SWMM model. With respect to the infiltration component of the water budget, Chui and Trinh (2016) showed that watershed-scale infiltration could be shifted toward pre-development conditions via application of infiltration-based practices such as bioretention across a 160-km^2 watershed in Singapore; however, ET still lagged. This model result echoed field observations from Bhaskar, Hogan, and Archfield, 2016 (2016). Still, as demonstrated by Wella-Hewage et al. (2016), the net effect of hydrologic regulation through LID may be sufficient to restore predevelopment channel forming flow regimes, that is, the duration and magnitude of flows responsible for the majority of geomorphic work in channels, even in cases of high urbanization

Several studies utilized models to better understand the capacity to mitigate flooding associated with extreme events and climate change. Effects of LID approaches on pluvial flooding ranged from minimal (Dudula and Randhir, 2016) to substantial (Ahiablame and Shakya, 2016), perhaps reflecting variability in flood response as a function of watershed size and extent to which simulated LID practices were implemented. Moore et al. (2016) used SWMM to predict LID impacts upon storm sewer surcharge and localized flooding in residential watersheds with differing development patterns and found that, in addition to structural LID practices such as bioretention, non-structural green infrastructure networks were a critical element in increasing adaptive capacity of developed areas to climate change. Similarly, the potential to alleviate localized flooding under climate change scenarios in which permeable pavements were sited using a GIS-based spatial optimization model was also demonstrated (Jato-Espino et al., 2016). Although not specifically set in the context of climate change, another study focused on flood mitigation by LID for less frequent events (2- to 10-year storm; 50 to 75 mm) in Columbia, SC and reported that treating 15-40% of impervious surface runoff in household rain gardens could achieve adequate mitigation (Morsy et al., 2016). Through development of treatment runoff volume performance curves for a variety of stormwater treatment and control practices, Hoss et al. (2016) demonstrated that infiltration-based practices performed better than detention-based practices over a wider range of operating conditions, suggesting LID approaches are better suited to managing stormwater under future climate uncertainty. However, flood mitigation performance is highly sensitive to the AMC of soils/media. For example, in modeling the capacity of greenroofs to mitigate peak runoff flow and volume from extreme events at the city-scale, both Masseroni and Cislaghi (2016) and Schmitter et al. (2016) reported negligible impacts unless media was near its permanent wilting point.

Spatial optimization of LID placement at the watershed-scale continues to be an area of interest (Duan, Li et al., 2016). For example, Liu, Bralts, et al. (2016) applied the L-THIA-LID 2.1 hydrologic model and the AMALGAM multi-algorithm method to examine differences in the cost to achieve target pollutant load and volume reductions for random versus spatially optimized placement of LID practices. The authors found optimizing placement reduced costs by a factor of 4 to 14. A high resolution gridded model, L-GriD, was developed and applied to demonstrate the potential to achieve greater hydrologic benefits by locating LID practices adjacent to roads rather than clustering in a particular area of the watershed (Zellner et al., 2016). Economic cost and payback period (as associated with avoided stormwater runoff) were also considered in watershed-scale stormwater optimization schemes. In a case study using the L-THIA-LID model, Wright et al. (2016) reported pay back periods of less than 1 to 17 years for cisterns and 15 to 40 years for bioretention retrofits to a neighborhood in Lafayette, IN. Similarly, Sun et al. (2016) found that a combination of detention and infiltration-based stormwater treatment practices was the most cost effective approach to manage runoff associated with future development and more extreme precipitation patterns using the EPA SUSTAIN decision support tool.

While economic costs and hydrologic/water quality benefits have been retained as the primary objective functions in watershed-scale LID optimization studies, there is increasing effort to consider broader environmental impacts and benefits. To this end, Morales-Torres et al. (2016) presented E^2STORMED, a decision support tool that builds upon capabilities of existing models by incorporating a more complete suite of energy and environmental benefits within multi-criteria analysis of stormwater management scenarios. Similarly, life cycle assessment models were developed to demonstrate that LID may outperform traditional stormwater management approaches (e.g., subsurface pipes and storage tanks) across a variety of environmental impact metrics by orders of magnitude (Brudler et al., 2016; Hengen et al., 2016). However, the relative magnitude of environmental impacts of conventional water systems to LID-based approaches is likely to vary with climate characteristics and population density (Jeong et al., 2016).

Implications to watershed-scale planning and implementation. While studies such as these demonstrate the potential to address urban stream degradation and other watershed-scale issues through LID, there remain numerous biophysical and social-institutional challenges to implementation at an appropriate scale (Vietz et al., 2016). Among the biophysical challenges is the variability of stream ecosystem response to urbanization and subsequent runoff mitigation arising from complexities in hydrologic processes at the watershed scale (Aryal et al., 2016; Bhaskar, Beesley, et al., 2016; Walsh et al., 2016). Such variability precludes generalization of watershed-scale planning across regions and, likely, watersheds within the same region. To address this challenge, Walsh et al. (2016) proposed an urban drainage typology that could be coupled with more general metrics (e.g., total or effective impervious area) to potentially improve predictions of urban development and stormwater management efforts on stream ecosystem health. Other efforts to untangle the complex effects of watershed characteristics on streamflow responses included development of a relatively simple tool to allow stormwater planners and managers to assess potential effects of development and stormwater management interventions on stream baseflow (Bhaskar, Beesley, Burns et al., 2016).

Of course, stormwater management plans based even on the best available decision support tools and underlying science are not effective unless implemented. Failure to implement stormwater planning policies was among the reasons posited to drive a positive association between watershed peak runoff and quality of community stormwater plans within the Chesapeake Watershed (Kim and Li, 2016). In addition to developing mechanisms to track implementation by planning agencies, clear communication of the costs and achievable benefits of LID on a watershed-specific basis may also promote implementation (e.g., Sun et al., 2016; Wright et al., 2016). As indicated by the growing interest in broader environmental impacts associated with stormwater management (e.g., Brundler et al., 2016), non-market environmental costs and benefits should also be included in decision support tools used to set stormwater policy (Morales-Torres et al., 2016). Actions at the household level have the potential to augment policy and other government-level interventions. For example, a coupled social-hydrologic model of household participation in rain garden and water harvesting programs indicated an additional 5-6% reduction in peak flow and volume could be achieved for a case study watershed in Syracuse, NY (Sun and Hall, 2016). Nemes et al. (2016) presented a framework for a market-based approach in which both the public and private supply of environmental services and impact of stormwater interventions on these services across scales was considered. The results of "Stormwater Tender," an auction-based field trial of this framework implemented in Melbourne, Australia in which individuals set the minimum price they would be willing to receive to install raingardens or rainwater tanks, was also presented. Despite existing limitations to predict bidders' behavior, this approach was shown to increase the cost effectiveness of stormwater management at the watershed.

Common Themes and Future Work. To continue closing the knowledge gap in understanding LID influences at the watershed scale, nearly all of these studies call for additional monitoring and field assessment of watershed-scale impacts. This need could be partially met by lower-cost monitoring approaches such as water level loggers (Toran, 2016). To date, the majority of watershed-scale LID assessments have been conducted in temperate climates. Additional work is needed to better understand optimal implementation of LID for stormwater management under hydrologic extremes presented in both tropical (Chui et al., 2016; Lim et al., 2016; Schmitter et al., 2016) and arid (Feng et al., 2016) climes. In addition, standardization of metrics used to characterize the drivers of stream degradation and other watershed-scale impacts of stormwater runoff and management strategies is needed (Walsh et al., 2016). Finally, several studies also identified the need to better understand opportunities for and benefits of stream restoration, particularly to more dynamic and geomorphically complex urban stream systems, as a component of watershed-scale LID to meet watershed quality goals (Lim et al., 2016; Vietz et al., 2016).

Other unclassified innovations

Several research topics were identified that did not fit within the preceding categories, but that warrant review as they fill novel niches within the broader body of stormwater research. Papers in this section span topics related to the development of innovative materials for stormwater filtration, optimization of stormwater treatment trains, quantification of non-structural LID practices, and linkages between social factors and stormwater quality. In addition to papers addressing enhanced media for bioretention systems as reviewed in the Bioretention section, six other papers were identified in which specialized sorbents and other filtration media were assessed for their general applicability to remove metals (Genc-Fuhrman et al., 2016; Huber, Hilbig, et al., 2016; Soleimanifar et al., 2016), nutrients (Rad et al., 2016; Soleimanifar et al., 2016), organic contaminants (Grebel et al., 2016), and bacteria (Wang, Feng et al., 2016). For example, wood mulch coated with aluminum-based water treatment residuals acted as a filtration media with high affinity for metals and desirable hydraulic characteristics (Soleimanifar et al., 2016). The potential to photodegrade both nutrients (Rad et al., 2016) and *E. coli* (Wang, Feng et al., 2016) though stormwater exposure to nano-titanium dioxide (TiO_2) and UV light was also demonstrated. Recovery of TiO_2 nanoparticles, a concern raised in previous studies, was enhanced through combination with graphene oxide nanosheets to increase the size, and thereby sedimentation rate and recovery potential, of TiO_2 particles. Environmental conditions under which pollutants may desorb from various filtration materials were also investigated (Grebel et al., 2016; Huber, Hilbig, et al., 2016; Genç-Fuhrman et al., 2016). Although response varied by material type, these studies suggest that exposure to road salts, particularly combinations of sodium and calcium chlorides, humic acids, and non-neutral pH, any of which can be expected in stormwater runoff, may promote pollutant remobilization from filtration materials.

One study specifically addressed design challenges associated with stormwater treatment trains by developing an optimization model framework to identify a set of near optimal combinations of types and sizes of stormwater practices in which annual life cycle costs were minimized while target nutrient removals and available land area constraints were met (Jayasooriya et al., 2016). A broader suite of economic, environmental, and social metrics was then applied to this near-optimal set to identify treatment train combinations with the highest performance across the so-called Triple Bottom Line. Whether operating as a single practice or as part of a treatment train, Lefkowitz et al. (2016) presented a system for continuous monitoring and adaptive control by actively managing system hydraulics (typically via an actuated valve controlling the outflow) based on real-time weather data. The potential to optimize the design and function of stormwater treatment practices through application of this technology was then demonstrated via a series of case studies illustrating, for example, the ability to use weather forecasts to trigger releases from CSWs or rainwater harvesting systems to create additional storage volume for forecasted storm events.

Three studies highlighted current efforts to quantify the role of urban trees in regulating stormwater quality and quantity. Transpiration from trees was estimated to account for 46 to 72% of runoff outputs from a bioswale in Illinois, with tree species characterized by high stomatal conductance and large size at maturity performing the best (Scharenbroch et al., 2016). In a mesocosm study designed to mimic application of trees in tree pits or biofilters, Denman et al. (2016) found that columns planted with trees significantly reduced stormwater dissolved nitrogen and phosphorus loads, while unplanted controls acted as a nutrient source. However, leaf fall from urban trees to impervious surfaces should be managed; Selbig (2016) found that over half of the annual P load from an urban watershed originated from phosphorus leached from leaves when leaf litter removal practices were not in place, compared to only 16% in a watershed in which street sweeping was employed. Other non-structural LID practices that were assessed in 2016 included downspout disconnection, which Carmen et al. (2016) found reduced runoff volume by 50-99% across a wide range of rooftop loading ratios, slope, length, and soil type, and subsoiling with organic amendments, a practice which was shown to support significantly higher infiltration rates and improved turf condition relative to standard urban landscape preparation of mass grading, compaction and topsoiling (Schwartz and Smith, 2016). The authors of both studies highlighted the relative effectiveness of these non-structural practices given their low cost and marginal changes to standard development strategies required to implement. Finally, the influence of social norms on stormwater quality was highlighted through a case study of household landscaping practices and preferences in a highly educated Florida community (Persaud et al., 2016). Despite a high awareness among homeowners of the ecological amenity value of water bodies in their communities, few demonstrated a high willingness to change landscape fertilization practices or support establishment of littoral vegetation, particularly if such practices were perceived to affect property value or diverge from social expectations. This finding suggests that, in addition to education, there is a need to strengthen linkages between social norms and environmental stewardship to enable further progress in stormwater management.

Conclusions

As evidenced by the volume of studies published in 2016, stormwater treatment and control has remained an active area of research. While this review spanned a variety of topics within the realm of stormwater treatment and control – including general characterization of stormwater quality and quantity, modeling and assessment of engineered practices for stormwater treatment and control, and watershed-scale impacts of these practices – several common research themes and needs emerged. Whether conducted at the mesocosm or watershed scale, many studies indicated the need to improve current mechanistic understandings of stormwater pollutant transport and treatment to improve representation of these processes in models and better predict treatment performance across time and space and under a variety of environmental and operational conditions. Such understanding will enhance efforts to optimize performance by various stormwater treatment and control practices, which, as indicated by the number of papers published in 2016 focused on targeting specific pollutant and hydrologic performance metrics, is another area of active research across the stormwater field. Additional testing of optimized design approaches – which may include biological components such as vegetation and/or physicochemical components such as specialized filtration media and active hydraulic controls – at the lab and field scales is needed. A growing number of studies considering LID performance in tropical and arid study sites and under extreme rainfall events in 2016 indicates increased interest to quantify the performance of infiltration-based stormwater practices under a wide range of climatic conditions. Finally, although only five papers in this review specifically addressed social-institutional aspects of stormwater management, the importance of underlying social norms and beliefs to the successful implementation and maintenance of stormwater treatment and control practices, particularly at the watershed scale, continued to be emphasized and, alongside biophysical factors, should continue to receive attention from the research community.

References

Abdul-Aziz, O. I.; Al-Amin, S. (2016). Climate, Land Use and Hydrologic Sensitivities of Stormwater Quantity and Quality in a Complex Coastal-Urban Watershed. *Urban Water J.*, *13*(3), 302-320.

Adyel, T. M.; Oldham, C. E.; Hipsey, M. R. (2016). Stormwater Nutrient Attenuation in a Constructed Wetland with Alternating Surface and Subsurface Flow Pathways: Event To Annual Dynamics. *Water Res.*, *107*, 66-82.

Ahiablame, L.; Shakya, R. (2016). Modeling Flood Reduction Effects of Low Impact Development at a Watershed Scale. *J. Environ. Manage.*, **171**, 81-91.

Ajmal, M.; Ahn, J.; Kim, T. (2016). Excess Stormwater Quantification in Ungauged Watersheds Using an Event-Based Modified NRCS Model. *Water Resour. Manage.*, **30**(4), 1433-1448.

Al Ali, S.; Bonhomme, C.; Chebbo, G. (2016). Evaluation of the Performance and the Predictive Capacity of Build-Up and Wash-Off Models on Different Temporal Scales. *Water*, **8**(8)

Al-Rubaei, A. M.; Engström, M.; Viklander, M.; Blecken, G. (2016). Long-Term Hydraulic and Treatment Performance of a 19-Year Old Constructed Stormwater Wetland—Finally Maturated or in Need of Maintenance? *Ecol. Eng.*, **95**, 73-82.

Aloisio, J.; Tuininga, A.; Lewis, J. (2016). Crop Species Selection Effects on Stormwater Runoff and Edible Biomass in an Agricultural Green Roof Microcosm. *Ecol. Eng.*, **88**, 20-27.

Alyaseri, I.; Zhou, J. (2016). Stormwater Volume Reduction in Combined Sewer Using Permeable Pavement: City of St. Louis. *J. Environ. Eng.*, **142**(4), 4016002-1-4016002-9.

Andradóttir, H. Ó.; Mortamet, M. (2016). Impact of Wind on Storm-Water Pond Hydraulics. *J. Hydraul. Eng.*,**142**(10).

Antunes, L. N.; Thives, L. P.; Ghisi, E. (2016). Potential for Potable Water Savings in Buildings by Using Stormwater Harvested From Porous Pavements. *Water*, **8**(4), 110.

Aryal, S. K.; Ashbolt, S.; McIntosh, B. S.; Petrone, K. P.; Maheepala, S.; Chowdhury, R. K.; Gardener, T.; Gardiner, R. (2016). Assessing and Mitigating the Hydrological Impacts of Urbanisation in Semi-Urban Catchments Using the Storm Water

Management Model. *Water Resour. Manage.*, **30**(14), 5437-5454.

Avila, H.; Avila, L.; Sisa, A. (2016) Dispersed Storage As Stormwater Runoff Control in Consolidated Urban Watersheds with Flash Flood Risk. *J. Water Resour. Plan. Manage.*, **142**(12), 1-8.

Bell, C. D.; McMillan, S. K.; Clinton, S. M.; Jefferson, A. J. (2016) Hydrologic Response To Stormwater Control Measures in Urban Watersheds. *J. Hydrol.*, **541**, 1488-1500.

Belayutham, S.; Gonzalez, V. A.; Yiu, T. W. (2016). A Cleaner Production-Pollution Prevention Based Framework for Construction Site Induced Water Pollution. *J. Clean. Prod.*, **135**, 1363-1378.

Bentarzi, Y.; Ghenaim, A.; Terfous, A.; Wanko, A.; Feugeas, F.; Poulet, J. B.; Mosé, R. (2016). Hydrodynamic Behaviour of A New Permeable Pavement Material Under High Rainfall Conditions. *Urban Water J.*, **13**(7), 687-696.

Bhaskar, A. S.; Beesley, L.; Burns, M. J.; Fletcher, T. D.; Hamel, P.; Oldham, C. E.; Roy, A. H. (2016). Will it Rise or Will it Fall? Managing the Complex Effects of Urbanization on Base Flow. *Freshwater Sci.*, **35**(1), 293-310.

Bhaskar, A. S.; Hogan, D. M.; Archfield, S. A. (2016). Urban Base Flow with Low Impact Development. *Hydrol. Process.*, **30**(18), 3156-3171.

Blair, A.; Sanger, D. (2016). Climate change and watershed hydrology-heavier precipitation influence on stormwater runoff. *Geosciences*, **6**(3).

Borris, M.; Österlund, H.; Marsalek, J.; Viklander, M. (2016). Contribution of Coarse Particles From Road Surfaces To Dissolved and Particle-Bound Heavy Metal Loads in Runoff: A Laboratory Leaching Study with Synthetic Stormwater. *Sci. Total Environ.*, **573**, 212-221.

Brink, I. C.; Kamish, W. (2016a). Stormwater Pond Metals and Solids Removal Efficiency Determination with the Effluent Probability Method: A Novel Classification System. *J. South Afr. Inst. Civil Eng.*, 58(2), 49-55.

Brink, I. C.; Kamish, W. (2016b). Stormwater Pond Efficiency Determinations with the Effluent Probability Method: the Use of Mass Versus Concentration Parameters. *J. South Afr. Inst. Civil Eng.*, 58(2), 42-48.

Brown, S.; Corfman, A.; Mendrey, K.; Kurtz, K.; Grothkopp, F. (2016). Stormwater Bioretention Systems: Testing the Phosphorus Saturation Index and Compost Feedstocks as Predictive Tools for System Performance. *J. Environ. Qual.*, **45**(1), 98.

Brudler, S.; Arnbjerg-Nielsen, K.; Hauschild, M. Z.; Rygaard, M. (2016). Life Cycle Assessment of Stormwater Management in the Context of Climate Change Adaptation. *Water Res.*, **106**, 394-404.

Brunetti, G.; Šimunek, J.; Piro, P. (2016). A Comprehensive Numerical Analysis of the Hydraulic Behavior of A Permeable Pavement. *J. Hydrol.*, **540**, 1146-1161.

Campisano, A.; Modica, C. (2016). Rainwater Harvesting As Source Control Option To Reduce Roof Runoff Peaks To Downstream Drainage Systems. *J. Hydroinform.* **18** (1), 23-32.

Carmen, N. B.; Hunt, W. F.; Anderson, A. R. (2016). Volume Reduction Provided by Eight Residential Disconnected Downspouts in Durham, North Carolina. *J. Environ. Eng.*,**142**(10).

Carpenter, C. M. G.; Todorov, D.; Driscoll, C. T.; Montesdeoca, M. (2016). Water Quantity and Quality Response of A Green Roof To Storm Events: Experimental and Monitoring Observations. *Environ. Poll.*, **218**, 664-672.

Cipolla, S.S.; Maglionico, M.; Stojkov, I. (2016). Experimental Infiltration Tests on Existing Permeable Pavement Surfaces. *Clean Soil Air Water* **1**, 89-95.

Chahal, M. K.; Shi, Z.; Flury, M. (2016). Nutrient Leaching and Copper Speciation in Compost-Amended Bioretention Systems. *Sci. Total Environ.*, **556**, 302-309.

Chandrappa, A.K.; Biligiri, K.P. (2016). Pervious Concrete as a Sustainable Pavement Material – Research Findings and Future Prospects: A State-of-the-Art Review. *Constr. Build. Mater.* **111**, 262-274.

Chandrasena, G. I.; Deletic, A.; McCarthy, D. T. (2016). Biofiltration for Stormwater Harvesting: Comparison of *Campylobacter* Spp. and *Escherichia Coli* Removal Under Normal and Challenging Operational Conditions. *J. Hydrol.*, **537**, 248-259.

Chang, J.J.; Yeih, W.; Chung, T.J.; Huang, R. (2016). Properties of Pervious Concrete Made with Electric Arc Furnace Slag and Alkali-Activated Slag Cement. *Constr. Build. Mater.* **109**, 34-40.

Charters, F. J.; Cochrane, T. A.; O'Sullivan, A. D. (2016). Untreated Runoff Quality From Roof and Road Surfaces in A Low Intensity Rainfall Climate. *Sci. Total Environ.*, **550**, 265-272.

Chen, R. H.; Li, F. P.; Zhang, H. P.; Jiang, Y.; Mao, L. C.; Wu, L. L.; Chen, L. (2016). Comparative Analysis of Water Quality and Toxicity Assessment Methods for Urban Highway Runoff. *Sci. Total Environ.*, **553**, 519-523.

Chiandet, A. S.; Xenopoulos, M. A. (2016). Landscape and Morphometric Controls on Water Quality in Stormwater Management Ponds. *Urban Ecosysts*, **19**(4), 1645-1663.

Chinen, K.; Lau, S.; Nonezyan, M.; McElroy, E.; Wolfe, B.; Suffet, I. H.; Stenstrom, M. K. (2016). Predicting Runoff Induced Mass Loads in Urban Watersheds: Linking Land Use and Pyrethroid Contamination. *Water Res.*, **102**, 607-618.

Chui, T.F.M.; Trinh, D.H. (2016). Modelling Infiltration Enhancement in A Tropical Urban Catchment for Improved Stormwater Management. *Hydrol. Process.*, **30**, 4405-4419.

Chunlin, L.; Miao, L.; Yuanman, H.; Jiping, G.; Yanyan, X. (2016). Modeling the Quality and Quantity of Runoff in a Highly Urbanized Catchment Using Storm Water Management Model. *Pol. J. Environ. Stud.*, **25**(4), 1573-1581.

Cipolla, S. S.; Maglionico, M.; Stojkov, I. (2016). A Long-Term Hydrological Modelling of an Extensive Green Roof by Means of SWMM. *Ecol. Eng.*, **95**, 876-887.

Corstanje, R.; Grafius, D.; Zawadzka, J.; Moreira Barradas, J.; Vince, G.; Ivanoff, D.; Pietro, K. (2016). A Datamining Approach To Identifying Spatial Patterns of Phosphorus Forms in the Stormwater Treatment Areas in the Everglades, US. *Ecol. Eng.*, **97,** 567-576.

Coutinho, A.P.; Lassabatere, L.; Montenegro, S.; Antonino, A.C.D.; Angulo-Jaramillo, R.; Cabral, J.J.S.P. (2016). Hydraulic Characterization and Hydrological Behaviour of A Pilot Permeable Pavement in an Urban Centre, Brazil. *Hydrol. Process*. **30**, 4242-4254.

Dagenais, D.; Thomas, I.; Paquette, S. (2016). Siting Green Stormwater Infrastructure in A Neighbourhood To Maximise Secondary Benefits: Lessons Learned From A Pilot Project. *Landscape Res.*, **42**(2), 195-210.

Dai, C.; Guo, H.C.; Tan, Q.; Ren, W. (2016). Development of A Constructed Wetland Network for Mitigating Nonpoint Source Pollution Through A GIS-Based Watershed-Scale Inexact Optimization Approach. *Ecol. Eng.*, **96**, 94-108.

Dallman, S.; Chaudhry, A. M.; Muleta, M. K.; Lee, J. (2016). The Value of Rain: Benefit-Cost Analysis of Rainwater Harvesting Systems. *Water Resour. Manage.*, **30**(12), 4415-4428.

Deng, Y.; Morris, C.; Rakshit, S.; Landa, E.; Punamiya, P.; Sarkar, D. (2016). Water Treatment Residuals and Scrap Tire Rubber As Green Sorbents for Removal of Stormwater Metals. *Water Environ. Res.*, **88**(6), 500-509.

Denman, E. C.; May, P. B.; Moore, G. M. (2016). The Potential Role of Urban Forests in Removing Nutrients from Stormwater. *J. Environ. Qual.*, **45**(1), 207.

Dietz, M. E. (2016). Modified Bioretention for Enhanced Nitrogen Removal from Agricultural Runoff. *J. Environ. Eng.*, **142**(12), 06016007.

Djukić, A.; Lekić, B.; Rajaković-Ognjanović, V.; Veljović, D.; Vulić, T.; Djolić, M.; Prodanović, D. (2016). Further Insight Into the Mechanism of Heavy Metals Partitioning in Stormwater Runoff. *J. Environ. Manage.*, **168**, 104-110.

Donald, W.N., Zech, W.C., Fang, F. Perez, M.A. (2016). Hydraulic Method To Evaluate the Performance of Ditch Check Practices and Products. *J. Hydrol. Eng.*, **21**(11).

Donovan, G. H.; Butry, D. T.; Mao, M. Y. (2016). Statistical Analysis of Vegetation and Stormwater Runoff in an Urban Watershed During Summer and Winter Storms in Portland, Oregon, U.S. *Arboricult. Urban Forest.*, **42**(5), 318-328.

Drake, J.; Dean, Y.; McIntosh, N. (2016). Performance of an Underground Stormwater Detention Chamber and Comparison with Stormwater Management Ponds. *Water*, **8**(5), 211.

Duan, H.; Li, F.; Yan, H. (2016). Multi-Objective Optimal Design of Detention Tanks in the Urban Stormwater Drainage System: LID Implementation and Analysis. *Water Resour. Manage.*, **30**(13), 4635-4648.

Duan, S.; Newcomer-Johnson, T.; Mayer, P., Kaushal, S. (2016). Phosphorus Retention in Stormwater Control Structures Across Streamflow in Urban and Suburban Watersheds. *Water*, **8**(9).

Dudula, J.; Randhir, T. O. (2016). Modeling the Influence of Climate Change on Watershed Systems: Adaptation Through Targeted Practices. *J. Hydrol.*, **541**, 703-713.

Ebrahimian, A.; Gulliver, J. S.; Wilson, B. N. (2016). Effective Impervious Area for Runoff in Urban Watersheds. *Hydrol. Process*., **30**(20), 3717-3729. doi:10.1002/hyp.10839

Elliott, R.; Gibson, R.; Carson, T.; Marasco, D.; Culligan, P.; McGillis, W. (2016). Green Roof Seasonal Variation: Comparison of the Hydrologic Behavior of A Thick and A Thin Extensive System in New York City. *Environ. Res. Lett.*, **11**(7), 074020.

Erickson, A. J.; Gulliver, J. S.; Arnold, W. A.; Brekke C.; and Bredal, M. (2016). Abiotic Capture of Stormwater Nitrates with Granular Activated Carbon. *Environ. Eng. Sci.*, **33**(5), 354-363.

Ezemonye, M. N.; Isueken, C. O.; Emeribe, C. N. (2016). Physicochemical and Bacteriological Characteristics of Rainwater Harvested from Rooftops in Esan-West Local Government Area of Edo State, Nigeria. *J. Appl. Sci. Environ. Manage.*, **20**(3), 748-757.

Feitosa, Castiglia R.; Wilkinson, S. (2016). Modelling Green Roof Stormwater Response for Different Soil Depths. *Landscape Urban Plan.*, **153**, 170-179.

Feng, Y.; Burian, S.; Pomeroy, C. (2016). Potential of Green Infrastructure To Restore Predevelopment Water Budget of A Semi-Arid Urban Catchment. *J. Hydrol.*, **542**, 744-755.

Fraga, I.; Charters, F. J.; O'Sullivan, A. D.; Cochrane, T. A. (2016). A Novel Modelling Framework To Prioritize Estimation of Non-Point Source Pollution Parameters for Quantifying Pollutant Origin and Discharge in Urban Catchments. *J. Environ. Manage.*, **167**, 75-84.

Gaborit, E.; Anctil, F.; Pelletier, G.; Vanrolleghem, P. A. (2016). Exploring Forecast-Based Management Strategies for Stormwater Detention Ponds. *Urban Water J.*, **13**(8), 841-851.

Gaitan, S.; van de Giesen, N. C.; ten Veldhuis, J. A. E. (2016). Can Urban Pluvial Flooding Be Predicted by Open Spatial Data and Weather Data? *Environ. Model. Softw.*, **85**, 156-171.

Galfi, H., Österlund, H., Marsalek, J., & Viklander, M. (2016). Indicator Bacteria and Associated Water Quality Constituents in Stormwater and Snowmelt From Four Urban Catchments. *J. Hydrol.*, **539**, 125-140.

Gao, Y.; Babin, N.; Turner, A. J.; Hoffa, C. R.; Peel, S.; Prokopy, L. S. (2016). Understanding Urban-

Suburban Adoption and Maintenance of Rain Barrels. *Landscape Urban Plan.*, **153**, 99-110.

Ge, Z.; Feng, C.; Wang, X.; Zhang, J. (2016). Seasonal Applicability of Three Vegetation Constructed Floating Treatment Wetlands for Nutrient Removal and Harvesting Strategy in Urban Stormwater Retention Ponds. *Int. Biodet. Biodegrad.*, **112**, 80-87.

Gee, K. D.; Hunt, W. F. (2016). Enhancing Stormwater Management Benefits of Rainwater Harvesting Via Innovative Technologies. *J. Environ. Eng.*, **142**(8).

Genç-Fuhrman, H.; Mikkelsen, P. S.; Ledin, A. (2016). Simultaneous Removal of As, Cd, Cr, Cu, Ni and Zn From Stormwater Using High-Efficiency Industrial Sorbents: Effect of Ph, Contact Time and Humic Acid. *Sci. Total Environ.*, **566**, 76-85.

GhaffarianHoseini, A.; Tookey, J.; GhaffarianHoseini, A.; Yusoff, S. M.; Hassan, N. B. (2016). State of the Art of Rainwater Harvesting Systems Towards Promoting Green Built Environments: A Review. *Desal. Water Treat.*, **57**(1), 95.

Grebel, J. E.; Charbonnet, J. A.; Sedlak, D. L. (2016). Oxidation of Organic Contaminants by Manganese Oxide Geomedia for Passive Urban Stormwater Treatment Systems. *Water Res.*, **88**, 481-491.

Gülbaz, S.; Kazezyılmaz-Alhan, C. M. (2016). Experimental Investigation on Hydrologic Performance of LID with Rainfall-Watershed-Bioretention System. *J. Hydrol. Eng.*, **22**(1), D4016003.

Guo, C.; Li, J.; Li, H.; Liang, Z. (2016). Soil Nitrogen Speciation and the Relationship with Microbial Biomass Carbon in Bioretention Tanks. *Water, Air, Soil Poll.*, **227**(12), 474.

Hathaway, J. M.; Winston, R. J.; Brown, R. A.; Hunt, W. F.; McCarthy, D. T. (2016). Temperature Dynamics of Stormwater Runoff in Australia and the USA. *Sci. Total Environ.*, **559**, 141-150.

Hartshorn, N.; Marimon, Z.; Xuan, Z.; Chang, N.; Wanielista, N.P. (2016). Effect of Floating Treatment Wetlands on Control of Nutrients in Three Stormwater Wet Detention Ponds. *J. Hydrol. Eng.*, **21**(8), 04016025.

Hartshorn, N.; Marimon, Z.; Xuan, Z.; Cormier, J.; Chang, N.; Wanielista, M. (2016). Complex Interactions Among Nutrients, Chlorophyll-A, and Microcystins in Three Stormwater Wet Detention Basins with Floating Treatment Wetlands. *Chemosphere,* **144**, 408-419.

Hengen, T. J.; Sieverding, H. L.; Stone, J. J. (2016) Lifecycle Assessment Analysis of Engineered Stormwater Control Methods Common to Urban Watersheds. *J. Water Resour. Plan. Manage.*, **142**(7), 1-9.

Hong, Y.; Bonhomme, C.; Le, M.; Chebbo, G. (2016). A New Approach of Monitoring and Physically-Based Modelling To Investigate Urban Wash-Off Process on A Road Catchment Near Paris. *Water Res.*, **102**, 96-108.

Hong, Y.; Bonhomme, C.; Ghassan C. (2016) Development and Assessment of the Physically-Based 2D/1D Model “TRENOE” for Urban Stormwater Quantity and Quality Modelling. *Water*, **8**(12), 1-18.

Horstmeyer, N.; Huber, M.; Drewes, J. E.; Helmreich, B. (2016). Evaluation of Site-Specific Factors Influencing Heavy Metal Contents in the Topsoil of Vegetated Infiltration Swales. *Sci. Total Environ.*, **560**, 19-28.

Hoss, F.; Fischbach, J.; Molina-Perez, E. (2016) Effectiveness of Best Management Practices for Stormwater Treatment as a Function of Runoff Volume. *J. Water Resour. Plan. Manage.*, **142**(11), 05016009

Huang, H.; Chow, C. W.; Jin, B. (2016). Characterisation of Dissolved Organic Matter in Stormwater Using High-Performance Size Exclusion Chromatography. *J. Environ. Sci.*, **42**, 236-245.

Huang, J.; He, J.; Valeo, C.; Chu, A. (2016). Temporal Evolution Modeling of Hydraulic and Water Quality Performance of Permeable Pavements. *J. Hydrol.*, **533**, 15-27.

Huang, J.; Valeo, C.; He, J.; Chu, A. (2016a). The Influence of Design Parameters on Stormwater Pollutant Removal in Permeable Pavements. *Water, Air, Soil Pollut.*, **227**(9).

Huang, J.; Valeo, C.; He, J.; Chu, A. (2016b). Three Types of Permeable Pavements in Cold Climates: Hydraulic and Environmental Performance. *J. Environ. Eng.*, **142**(6), 04016025.

Huber, M.; Badenberg, S. C.; Wulff, M.; Drewes, J. E.; Helmreich, B. (2016). Evaluation of Factors Influencing Lab-Scale Studies To Determine Heavy Metal Removal by Six Sorbents for Stormwater Treatment. *Water*, **8**(2), 62.

Huber, M.; Helmreich, B. (2016). Stormwater Management: Calculation of Traffic Area Runoff Loads and Traffic Related Emissions. *Water*, **8**(7), 1-21.

Huber, M.; Hilbig, H.; Badenberg, S. C.; Fassnacht, J.; Drewes, J. E.; Helmreich, B. (2016). Heavy Metal Removal Mechanisms of Sorptive Filter Materials for Road Runoff Treatment and Remobilization Under De-Icing Salt Applications. *Water Res.*, **102**, 453-463.

Huber, M.; Welker, A.; Dierschke, M.; Drewes, J. E.; Helmreich, B. (2016). A Novel Test Method To Determine the Filter Material Service Life of Decentralized Systems Treating Runoff From Traffic Areas. *J. Environ. Manage.*, **179**, 66-75.

Huber, M.; Welker, A.; Helmreich, B. (2016). Critical Review of Heavy Metal Pollution of Traffic Area Runoff: Occurrence, Influencing Factors, and Partitioning. *Sci. Total Environ.*, **541**, 895-919.

Jang, M. W.; Kim, D. H.; Jang, J. R.; Kim, S. M. (2016). A Plot-Scale Monitoring Experiment To Assess the Agricultural Nonpoint Source Pollution Reductions Achieved by Silt Fences and Berms. *Irrig. Drain.*, **65**, 182-192.

Jarden, K. M.; Jefferson, A. J.; Grieser, J. M. (2016). Assessing the Effects of Catchment-Scale Urban

Green Infrastructure Retrofits on Hydrograph Characteristics. *Hydrol. Process.*, **30**(10), 1536-1550.

Jato-Espino, D.; Sillanpää, N.; Charlesworth, S. M.; Andrés-Doménech, I. (2016). Coupling GIS with Stormwater Modelling for the Location Prioritization and Hydrological Simulation of Permeable Pavements in Urban Catchments. *Water*, **8**(10).

Jayasooriya, V. M.; Ng, A. W. M.; Muthukumaran, S.; Perera, B. J. C. (2016). Optimal Sizing of Green Infrastructure Treatment Trains for Stormwater Management. *Water Resour. Manage.*, **30**(14), 5407-5420.

Jelinkova, V.; Dohnal, M.; Sacha, J. (2016). Thermal and Water Regime Studied in A Thin Soil Layer of Green Roof Systems at Early Stage of Pedogenesis. *J. Soils Sed.*, **16**(11), 2568-2579.

Jennings; A. A. (2016). Residential Rain Garden Performance in the Climate Zones of the Contiguous United States. *J. Environ. Eng.*, **142**(12), 04016066.

Jennings, A. A.; Baker, K. (2016). Hydraulic Performance of a Residential Stormwater Infiltration Gallery. *J. Environ. Eng.*, **142**(3), 1-9.

Jeong, H.; Broesicke, O.A.; Drew, B.; Li, D.; Crittenden, J.C. (2016). Life Cycle Assessment of Low Impact Development Technologies Combined with Conventional Centralized Water Systems for the City of Atlanta, Georgia. *Front. Environ. Sci. Eng.*, **10**(6), 1-13.

Johannsen, L.L.; Cederkvist, K.; Holm, P.E.; Ingvertsen, S.T. (2016). Aluminum Oxide-Coated Sand for Improved Treatment of Urban Stormwater. *J. Environ. Qual.*, **45**, 720-727.

Johnson, C.; Schweinhart, S.; Buffam, I. (2016). Plant Species Richness Enhances Nitrogen Retention in Green Roof Plots. *Ecol. Appl.*, **26**(7), 2130-2144.

Johnson, J. J.; Hunt, W. W. (2016). Evaluating the Spatial Distribution of Pollutants and Associated Maintenance Requirements in an 11 Year-Old Bioretention Cell in Urban Charlotte, NC. *J. Environ. Manage.*, **184**, 363-370.

Kadlec, R. H. (2016). Large Constructed Wetlands for Phosphorus Control: A Review. *Water*, **8**(6).

Kalibova, J.; Jacka, L.; Petru, J. (2016). The Effectiveness of Jute and Coir Blankets for Erosion Control in Different Field and Laboratory Conditions. *Solid Earth*, **7**, 469-479.

Kang, J.; King, S. E.; McLaughin, R. A. (2016) Flocculated Sediments Can Reduce the Size of Sediment Basin at Construction Sites. *J. Environ. Manage.*, **156**(15), 450-456.

Karlsson, K.; Blecken, G.; Öhlander, B.; Viklander, M. (2016). Environmental Risk Assessment of Sediments Deposited in Stormwater Treatment Facilities: Trace Metal Fractionation and its Implication for Sediment Management. *J. Environ. Eng.*, **142**(11), 1-9.

Kim, H.W.; Li, M. (2016) Sustainable Stormwater Management: Examining the Role of Local

Planning Capacity in Mitigating Peak Surface Runoff. *Sustainability* **8**(9).

Kim, H. W.; Park, Y. (2016). Urban Green Infrastructure and Local Flooding: the Impact of Landscape Patterns on Peak Runoff in Four Texas MSAs. *Appl. Geog.*, *77*, 72-81.

Knighton, J. J.; Lennon, E. E.; Bastidas, L. L.; White, E. E. (2016). Stormwater Detention System Parameter Sensitivity and Uncertainty Analysis Using SWMM. *J. Hydrol. Eng.*, **21**(8), 1-15.

Kok, K. H.; Mohd Sidek, L.; Chow, M. F.; Zainal Abidin, M. R.; Basri, H.; Hayder, G. (2016). Evaluation of Green Roof Performances for Urban Stormwater Quantity and Quality Controls. *Int. J. River Basin Manage.*, **14**(1), 1-7.

Komkiene, J.; Baltrenaite, E. (2016). Biochar as Adsorbent for Removal of Heavy Metal Ions [Cadmium (II), Copper (II), Lead (II), Zinc (II)] From Aqueous Phase. *Int. J. Environ. Sci. Technol.*, **13**(2), 471-482.

Ku, J.; Jiaming, L.; Ulrich, A.; Yang, L. (2016). Sulfide Production and Management in Municipal Stormwater Retention Ponds. *J. Environ. Eng.*, **142**(2), 1.

Kumar, K.; Kozak, J.; Hundal, L.; Cox, A.; Zhang, H.; Granato, T. (2016). in-situ Infiltration Performance of Different Permeable Pavements in a Employee Used Parking Lot – A Four-Year Study. *J. Environ. Manage.*, **16**, 78-14.

Kuoppamäki, K.; Lehvävirta, S. (2016). Mitigating Nutrient Leaching From Green Roofs with Biochar. *Landscape Urban Plan.*, **152**, 39-48.

Kuoppamäki, K.; Hagner, M.; Lehvävirta, S.; Setälä, H. (2016). Biochar Amendment in the Green Roof Substrate Affects Runoff Quality and Quantity. *Ecol. Eng.*, **88**, 1-9.

LaBarre, W. J.; Ownby, D. R.; Lev, S. M.; Rader, K. J.; Casey, R. E. (2016). Attenuation of Copper in Runoff From Copper Roofing Materials by Two Stormwater Control Measures. *Water Res.*, **88**, 207-215.

Lancaster, N. A.; Bushey, J. T.; Tobias, C. R.; Song, B.; Vadas, T. M. (2016). Impact of Chloride on Denitrification Potential in Roadside Wetlands. *Environ. Poll.*, **212**, 216-223.

Launay, M. A.; Dittmer, U.; Steinmetz, H. (2016). Organic Micropollutants Discharged by Combined Sewer Overflows – Characterisation of Pollutant Sources and Stormwater-Related Processes. *Water Res.*, **104**, 82-92.

Lefkowitz, J.R.; Sarmanian, A.K.; Quigley, M. (2016). Continuous Monitoring and Adaptive Control – The Internet of Things Transforms Stormwater Management. *J. New England Water Eviron. Assoc.*, **50**(1), 44-51.

Leroy, M. C.; Portet-Koltalo, F.; Legras, M.; Lederf, F.; Moncond'huy, V.; Polaert, I.; Marcotte, S. (2016). Performance of Vegetated Swales for Improving Road Runoff Quality in a Moderate

Traffic Urban Area. *Sci. Total Environ.*, **566**, 113-121.

Leutnant, D.; Muschalla, D.; Uhl, M. (2016). Stormwater Pollutant Process Analysis with Long-Term Online Monitoring Data at Micro-Scale Sites. *Water*, **8**(7), 1-12.

Li, J.; Jiang, C; Lei, T.; Li, Y. (2016). Experimental Study and Simulation of Water Quality Purification of Urban Surface Runoff Using Non-Vegetated Bioswales. *Ecol. Eng.*, **95**, 706-713.

Li, J.; Li, Y.; Zhang, J.; Li, Y. (2016). Bioswale Column Experiments and Simulation of Pollutant Removal From Urban Road Stormwater Runoff. *Desal. Water Treat.,* **57**(52), 24894-24912.

Li, Y.; Babcock, R. W. (2016). A Simplified Model for Modular Green Roof Hydrologic Analyses and Design. *Water,* **8**(8).

Li, Y.; Mccarthy, D. T.; Deletic, A. (2016). *Escherichia Coli* Removal in Copper-Zeolite-Integrated Stormwater Biofilters: Effect of Vegetation, Operational Time, Intermittent Drying Weather. *Ecol. Eng.*, **90**, 234-243.

Lim, H.; Lu, X. (2016). Sustainable Urban Stormwater Management in the Tropics: an Evaluation Singapore's ABC Waters Program. *J. Hydrol.*, **53***(8),* 842-862.

Liu, Y.; Bralts, V.F.; Chaubey, I.; Bowling, L.C.; Engel, B.A. (2016). Optimal Selection and Placement of BMPs and LID Practices with a Rainfall-Runoff Model. *Environ. Model. Softw.* **80**: 281-296.

Liu, A.; Gunawardana, C.; Gunawardena, J.; Egodawatta, P.; Ayoko, G. A.; Goonetilleke, A. (2016). Taxonomy of Factors Which Influence Heavy Metal Build-Up on Urban Road Surfaces. *J. Haz. Mat.*, **310**, 20-29.

Liu, L.; Liu, A.; Li, Y.; Zhang, L.; Zhang, G.; Guan, Y. (2016). Polycyclic Aromatic Hydrocarbons Associated with Road Deposited Solid and Their Ecological Risk: Implications for Road Stormwater Reuse. *Sci. Total Environ.*, **563-564**, 190-198.

Liu, R.; Coffman, R. (2016). Lightweight Aggregate Made From Dredged Material in Green Roof Construction for Stormwater Management. *Materials*, **9**(8), 1-16.

Liu, R.; Fassman-Beck, E. E. (2016). Effect of Composition on Basic Properties of Engineered Media for Living Roofs and Bioretention. *J. Hydrol. Eng.*, **21**(6), 1-6.

Logsdon, S. D.; Sauer, P. A. (2016a). Iron Filings Cement Engineered Soil Mix. *Agron. J.*, **108**(4), 1753-1557.

Logsdon, S. D.; Sauer, P. A. (2016b). Nutrient Leaching When Compost is Part of Plant Growth Media. *Compost Sci. Util.*, **24**(4), 238-245.

Ludwig, A.; Hession, W. C.; Scott, D.; Gallagher, D. (2016). Simulated Flood of a Small Constructed Floodplain Wetland in Virginia: Event-Scale Pollutant Attenuation. *Trans. ASABE*, **59**(5), 1321-1331.

Lusk, M. G.; Toor, G. S. (2016). Biodegradability and Molecular Composition of Dissolved Organic Nitrogen in Urban Stormwater Runoff and Outflow Water From a Stormwater Retention Pond. *Environ. Sci. Technol.*, **50**(7), 3391-3398.

Ma, Y.; Egodawatta, P.; Mcgree, J.; Liu, A.; Goonetilleke, A. (2016). Human Health Risk Assessment of Heavy Metals in Urban Stormwater. *Sci. Total Environ.*, **557**, 764-772.

Mackintosh, T.J.; Davis, J.A.; Thompson, R.M. (2016a) Impacts of Multiple Stressors on Ecosystem Function: Leaf Decomposition in Constructed Urban Wetlands. *Environ. Poll.* **208**, 221-232.

Mackintosh, T. J.; Davis, J. A.; Thompson, R. M. (2016b) Tracing Metals Through Urban Wetland Food Webs. *Ecol. Eng.*, **94**, 200-213.

Maniquiz-Redillas, M. C.; Kim, L. (2016). Evaluation of The Capability of Low-Impact Development Practices for the Removal of Heavy Metal From Urban Stormwater Runoff. *Environ. Technol.*, **37**(18), 2265-2272.

Manka, B. N.; Hathaway, J. M.; Tirpak, R. A.; He, Q.; Hunt, W. F. (2016). Driving Forces of Effluent Nutrient Variability in Field Scale Bioretention. *Ecol. Eng.*, **94**, 622-628.

Marois, D. E.; Mitsch, W. J. (2016). Modeling Phosphorus Retention at Low Concentrations in Florida Everglades Mesocosms. *Ecol. Model.*, **319**, 42-62.

Masseroni, D.; Cislaghi, A. (2016). Green Roof Benefits for Reducing Flood Risk at the Catchment Scale. *Environ Earth Sci*, **75**(7), 579-590.

Mbuanaso, F. U.; Nnadi, E. O.; Coupe, S. J.; Charlesworth, S. M. (2016). Stormwater Harvesting Rom Landscaped Areas: Effect of Herbicide Application on Water Quality and Usage. *Environ. Sci. Pollut. Res.*, **23**, 15970-15982.

Mcandrew, B.; Ahn, C.; Spooner, J. (2016). Nitrogen and Sediment Capture of a Floating Treatment Wetland on an Urban Stormwater Retention Pond-the Case of the Rain Project. *Sustainability*, **8**(10), 972.

Mcintyre, J. K.; Edmunds, R. C.; Redig, M. G.; Mudrock, E. M.; Davis, J. W.; Incardona, J. P.; Startk, J. D.; Scholz, N. L. (2016). Confirmation of Stormwater Bioretention Treatment Effectiveness Using Molecular Indicators of Cardiovascular Toxicity in Developing Fish. *Environ. Sci. Technol.*, **50**(3), 1561-1569.

Mehring, A. S.; Hatt, B. E.; Kraikittikun, D.; Orelo, B. D.; Rippy, M. A.; Grant, S. B.; Gozalez, J. P.; Jiang, S. C.; Ambrose, R. F.; Levin, L. A. (2016). Soil Invertebrates in Australian Rain Gardens and Their Potential Roles in Storage and Processing of Nitrogen. *Ecol. Eng.*, **97**, 138-143.

Melville-Shreeve, P.; Ward, S.; Butler, D. (2016). Rainwater Harvesting Typologies for UK Houses: A Multi Criteria Analysis of System Configurations. *Water*, **8**(4), 1-18.

Merriman, L. S.; Hunt, W. F.; Bass, K. L. (2016). Development/Ripening of Ecosystems Services in the First Two Growing Seasons of a Regional-Scale Constructed Stormwater Wetland on the Coast of North Carolina. *Ecol. Eng.*, **94**, 393-405.

Miles, T. R.; Rasmussen, E. M.; Gray, M. (2016). Aqueous Contaminant Removal and Stormwater Treatment Using Biochar. in: M. Guo, Z. He, S. M. Uchimiya, editors, *Agricultural and Environmental Applications of Biochar: Advances and Barriers*, SSSA Spec. Publ. 63. SSSA, Madison, WI, 341-376

Monaghan, P.; Hu, S.; Hansen, G.; Ott, E.; Nealis, C.; Morera, M. (2016). Balancing the Ecological Function of Residential Stormwater Ponds with Homeowner Landscaping Practices. *Environ. Manage.*, **58**(5), 843-856.

Monteiro, C. M.; Calheiros, C. C.; Pimentel-Rodrigues, C.; Silva-Afonso, A.; Castro, P. L. (2016). Contributions To the Design of Rainwater Harvesting Systems in Buildings with Green Roofs in a Mediterranean Climate. *Water Sci. Technol.*, **73**(8), 1842.

Moore, T. L.; Gulliver, J. S.; Stack, L.; Simpson, M. H. (2016) Stormwater Management and Climate Change: Vulnerability and Capacity for Adaptation in Urban and Suburban Contexts. *Climatic Change*, **138**(3-4), 491-504.

Morales-Torres, A.; Escuder-Bueno, I.; Andrés-Doménech, I.; Perales-Momparler, S. (2016). Decision Support Tool for Energy-Efficient, Sustainable and Integrated Urban Stormwater Management. *Environ. Model. Softw.*, **84**, 518-528.

Morsy, M. M.; Goodall, J. L.; Shatnawi, F. M.; Meadows, M. E. (2016). Distributed Stormwater Controls for Flood Mitigation within Urbanized Watersheds: Case Study of Rocky Branch Watershed in Columbia, South Carolina. *J. Hydrol. Eng.*, **21**(11).

Natarajan, P.; Davis, A. P. (2016a). Ecological Assessment of a Transitioned Stormwater Infiltration Basin. *Ecol. Eng.*, **90**, 261-267.

Natarajan, P.; Davis, A. P. (2016b). Performance of a 'Transitioned' Infiltration Basin Part 2: Nitrogen and Phosphorus Removals. *Water Environ. Res.*, **88**(4), 291-302.

Nemes, V.; La Nauze, A.; Walsh, C. J.; Fletcher, T. D.; Bos, D. G.; Ross, Rakesh, S.; Stoneham, G. (2016). Saving a Creek One Bid at a Time: A Uniform Price Auction for Urban Stormwater Retention. *Urban Water J.*, **13**(3), 232-241.

Nichols, P.; Lucke, T. (2016). Evaluation of the Long-Term Pollution Removal Performance of Established Bioretention Cells. *Int. J. Geomat.*, 11(24), 2363-2369.

Niu, S.; Park, K.; Cheng, J.; Kim, Y. (2016). an Investigation Into the Relationship Between Water Quality Volume (Design Storage Volume) and Stormwater Wetland Performance. *Water Sci. Technol.*, **73**(6), 1483-1491.

Niu, Z.; Lv, Z.; Zhang, Y.; Cui, Z. (2016). Stormwater Infiltration and Surface Runoff Pollution

Reduction Performance of Permeable Pavement Layers. *Env. Sci. Poll. Res.*, **23**(3), 2576-2587.

Palta, M. M.; Ehrenfeld, J. G.; Giménez, D.; Groffman, P. M.; Subroy, V. (2016). Soil Texture and Water Retention As Spatial Predictors of Denitrification in Urban Wetlands. *Soil Biol. Biochem.*, **101**, 237-250.

Nocco, M. A.; Rouse, S. E.; Balster, N. J. (2016). Vegetation Type Alters Water and Nitrogen Budgets in a Controlled, Replicated Experiment on Residential-Sized Rain Gardens Planted with Prairie, Shrub, and Turfgrass. *Urban Ecosyst.*, **19**(4), 1665-1691.

Paule-Mercado, M.; Ventura, J.; Memon, S.; Jahng, D.; Kang, J.; Lee, C. (2016). Monitoring and Predicting the Fecal Indicator Bacteria Concentrations From Agricultural, Mixed Land Use and Urban Stormwater Runoff. *Sci. Total Environ.*, **550**, 1171-1181.

Pelak, N.; Porporato, A. (2016). Sizing a Rainwater Harvesting Cistern by Minimizing Costs. *J. Hydrol.*, **541**, 1340-1347.

Peng, H.; Liu, Y.; Wang, H; Gao, X.; Ma, L. (2016). Event Mean Concentration and First Flush Effect From Different Drainage Systems and Functional Areas During Storms. *Environ. Sci. Poll. Res.*, **23**(6), 5390-5398.

Peng, J., Cao, Y., Rippy, M. A., Nabiul Afrooz, A. R. M., Grant, S. B. (2016). Indicator and Pathogen Removal by Low Impact Development Best Management Practices. *Water* **8**(600), 1-24.

Pennino, M. J.; Mcdonald, R. I.; Jaffe, P. R. (2016). Watershed-Scale Impacts of Stormwater Green Infrastructure on Hydrology, Nutrient Fluxes, and Combined Sewer Overflows in the Mid-Atlantic Region. *Sci. Total Environ.*, ***565***, 1044-1053.

Percot, S., Ruban, V., Roupsard, P., Maro, D., & Millet, M. (2016). A New Method for Assessing the Contribution of Atmospheric Deposition To the Stormwater Runoff Metal Load in a Small Urban Catchment. *Water, Air, Soil Poll.*, **227**(6), 1-13.

Perez, M. A., Zech, W. C., Donald, W. N., Fang, X. (2016a). Design Methodology for the Selection of Temporary Erosion and Sediment Control Practices Based on Regional Hydrological Conditions. *J. Hydrol. Eng.*, **21**(4).

Perez, M. A., Zech, W. C., Donald, W. N., Fang, X. (2016b). Sedspread: Sediment-Basin Design Tool for Construction Sites. *J. Irrig. Drain. Eng.*, **142**(12).

Perez, M. A.; Zech, W. C.; Fang, X.; Vasconcelos, J. G. (2016) Methodology and Development of a Large-Scale Sediment Basin for Performance Testing. *J. Irrig. Drain. Eng.* **142**(10).

Persaud, A.; Alsharif, K.; Monaghan, P.; Akiwumi, F.; Morera, M. C.; Ott, E. (2016). Landscaping Practices, Community Perceptions, and Social Indicators for Stormwater Nonpoint Source Pollution Management. *Sustain. Cities Soc.*, **27**, 377-385.

Petterson, S. R.; Mitchell, V. G.; Davies, C. M.; O'connor, J.; Kaucner, C.; Roser, D.; Ashbolt, N. (2016).

Evaluation of Three Full-Scale Stormwater Treatment Systems with Respect To Water Yield, Pathogen Removal Efficacy and Human Health Risk From Faecal Pathogens. *Sci. Total Environ.*, **543**(Part A), 691-702.

Pina, R. D.; Ochoa-Rodriguez, S.; Simões, N. E.; Mijic, A.; Sá Marques, A.; Maksimović, Č. (2016). Semi-Vs. Fully-Distributed Urban Stormwater Models: Model Set Up and Comparison with Two Real Case Studies. *Water*, **8**(2), 1-20.

Prosdocimi, M.; Tarolli, P.; Cerda, A. 2016. Mulching Practices for Reducing Soil Water Erosion: A Review. *Earth Sci. Rev.*, **161**, 191-203

Qin, H.; He, K.; Fu, G. (2016). Modeling Middle and Final Flush Effects of Urban Runoff Pollution in an Urbanizing Catchment. *J. Hydrol.*, **534**, 638-647.

Qin, Y.; Hiller, J.E. (2016) Water Availability Near the Surface Dominates the Evaporation of Pervious Concrete. *Constr. Build. Mater.* **111**, 77-84.

Rad, S.; Shamsudin, S.; Taha, M. R.; Shahid, S. (2016). Tropical Stormwater Nutrient Degradation Using Nano-Tio2 in Photocatalytic Reactor Detention Pond. *Water Sci. Technol.*, **73**(2), 405-413.

Radfar, A.; Rockaway, T. D. (2016a). Captured Runoff Prediction Model by Permeable Pavements Using Artificial Neural Networks. *J. Infrast. Syst.*, **22**(3).

Radfar, A.; Rockaway, T. D. (2016b). Clogging Prediction of Permeable Pavement. *J. Irrig. Drain Eng.* **142**(4), 04015069-1.

Rahman, M. A.; Imteaz, M. A.; Arulrajah, A. (2016). Suitability of Reclaimed Asphalt Pavement and Recycled Crushed Brick As Filter Media in Bioretention Applications. *Int. J. Environ. Sustain. Dev.* **15**(1), 32-48.

Randelovic, A.; Zhang, K.; Jacimovic, N.; Mccarthy, D.; Deletic, A. (2016). Stormwater Biofilter Treatment Model (MPIRE) for Selected Micro-Pollutants. *Water Res.*, **89**, 180-191.

Razak Al-Ani, I. A.; Wan Mohtar, W. H. M., Ahmad Basri, N. E.; Sidek, L. M. (2016). Development of a Hybrid Expert System-Multi Criteria Analysis on Erosion and Sediment Control in Construction Industry. *KSCE J. Civ. Eng.* **20**(7), 3045-3056.

Rodriguez-Hernandez, J.; Andrés-Valeri, V. C.; Ascorbe-Salcedo, A.; Castro-Fresno, D. (2016). Laboratory Study on the Stormwater Retention and Runoff Attenuation Capacity of Four Permeable Pavements. *J. Environ. Eng.*, **142**(2), 1-8.

Rycewicz-Borecki, M.; Mclean, J. E.; Dupont, R. R. (2016). Bioaccumulation of Copper, Lead, and Zinc in Six Macrophyte Species Grown in Simulated Stormwater Bioretention Systems. *J. Environ. Manage.*, **166**, 267-275.

Sabouri, F.; Gharabaghi, B.; Sattar, A. M. A.; Thompson, A. M. (2016). Event-Based Stormwater Management Pond Runoff Temperature Model. *J. Hydrol.*, **540**, 306-316.

Sadeghi, S. H.; Hazbavi, Z.; Younsi, H.; Bahramifar, N. (2016). Trade-Off Between Runoff and

Sediments From Treated Erosion Plots and Polyacrylamide and Acrylamide Residues. *Catena*, **142**, 213-220.

Scharenbroch, B.C.; Morgenroth, J.; Maule, B. (2016). Tree Species Sutability To Bioswales and Impact on the Urban Water Budget. *J. Environ. Qual.*, **45**(1), 199-206.

Scheffers, B. R.; Paszkowski, C. A. (2016). Large Body Size for Metamorphic Wood Frogs in Urban Stormwater Wetlands. *Urban Ecosyst.*, **19**(1), 347-359.

Schiff, K. C.; Tiefenthaler, L. L.; Bay, S. M.; Greenstein, D. J. (2016). Effects of Rainfall Intensity and Duration on the First Flush From Parking Lots. *Water*, **8**, 320.

Schifman, L. A.; Kasaraneni, V. K.; Sullivan, R. K.; Oyanedel-Craver, V.; Boving, T. B. (2016). Bacteria Removal From Stormwater Runoff Using Tree Filters: A Comparison of a Conventional and an Innovative System. *Water*, **8**(3), 1-16.

Schmitter, P.; Goedbloed, A.; Galelli, S.; Babovic, V. (2016). Effect of Catchment-Scale Green Roof Deployment on Stormwater Generation and Reuse in a Tropical City. *J. Water Res. Plan. Manage.*, **142**(7).

Schwartz, S. S.; Smith, B. (2016). Restoring Hydrologic Function in Urban Landscapes with Suburban Subsoiling. *J. Hydrol.*, **543**, 770-781.

Selbig, W. R. (2016). Evaluation of Leaf Removal As a Means To Reduce Nutrient Concentrations and Loads in Urban Stormwater. *Sci. Total Environ.*, **571**, 124-133.

Sharley, D. J.; Sharp, S. M.; Bourgues, S.; Pettigrove, V. J. (2016). Detecting Long-Term Temporal Trends in Sediment-Bound Trace Metals From Urbanised Catchments. *Environ. Poll.*, **219**, 705-713.

Sharma, A. K.; Vezzaro, L.; Birch, H.; Arnbjerg-Nielsen, K.; Mikkelsen, P. S. (2016). Effect of Climate Change on Stormwater Runoff Characteristics and Treatment Efficiencies of Stormwater Retention Ponds: A Case Study From Denmark Using Tss and Cu As Indicator Pollutants. *Springerplus* **5**, 1984.

She, Y.; Kemp, J.; Richards, L.; Loewen, M. (2016). Investigation Into Freezing Point Depression in Stormwater Ponds Caused by Road Salt. *Cold Reg. Sci. Tech*,, **13**, *1*53-64.

Shen, Z.; Liu, J.; Aini, G.; Gong, Y. (2016). A Comparative Study of the Grain-Size Distribution of Surface Dust and Stormwater Runoff Quality on Typical Urban Roads and Roofs in Beijing, China. *Environ. Sci. Poll. Res.*, **23**(3), 2693-2704**.**

Shimabuku, K. K.; Kearns, J. P.; Martinez, J. E.; Mahoney, R. B.; Moreno-Vasquez, L.; Summers, R. S. (2016). Biochar Sorbents for Sulfamethoxazole Removal From Surface Water, Stormwater, and Wastewater Effluent. *Water Res.*, **96**, 236-245.

Sims, A. W.; Robinson, C. E.; Smart, C. C.; Voogt, J. A.; Hay, G. J.; Lundholm, J. T.; O'carroll, D. M. (2016). Retention Performance of Green Roofs in

Three Different Climate Regions. *J. Hydrol.*, **542**, 115-124.

Søberg, L. C.; Vollertsen, J.; Blecken, G.; Nielsen, A. H.; Viklander, M. (2016). Bioaccumulation of Heavy Metals in Two Wet Retention Ponds. *Urban Water J.*, **13**(7), 697-709.

Soleimanifar, H.; Deng, Y.; Wu, L.; Sarkar, D. (2016). Water Treatment Residual (Wtr)-Coated Wood Mulch for Alleviation of Toxic Metals and Phosphorus From Polluted Urban Stormwater Runoff. *Chemosphere*, **154**, 289-292.

Sønderup, M. J.; Egemose, S.; Hansen, A. S.; Grudinina, A.; Madsen, M. H.; Flindt, M. R. (2016). Factors Affecting Retention of Nutrients and Organic Matter in Stormwater Ponds. *Ecohydrol.*, ***9***(5), 796-806.

Sounthararajah, D. P.; Loganathan, P.; Kandasamy, J.; Vigneswaran, S. (2016). Column Studies on the Removal of Dissolved Organic Carbon, Turbidity and Heavy Metals From Stormwater Using Granular Activated Carbon. *Desal. Water Treat.*, **57**(11), 5045-5055.

Starry, O.; Lea-Cox, J.; Ristvey, A.; Cohan, S. (2016). Parameterizing a Water-Balance Model for Predicting Stormwater Runoff From Green Roofs. *J. Hydrol. Eng.*, **21**(12)

Stephansen, D. A.; Nielsen, A. H.; Hvitved-Jacobsen, T.; Pedersen, M. L.; Vollertsen, J. (2016). Invertebrates in Stormwater Wet Detention Ponds — Sediment Accumulation and Bioaccumulation of Heavy Metals Have No Effect on Biodiversity and Community Structure. *Sci. Total Environ.*, **566-567**, 1579-1587.

Subramaniam, D. D.; Mather, P.; Russell, S.; Rajapakse, J. (2016). Dynamics of Nitrate-Nitrogen Removal in Experimental Stormwater Biofilters Under Intermittent Wetting and Drying. *J. Environ. Eng.*, **142**(3), 1-12.

Sultana, N.; Akib, S.; Ashraf, M.A.; Abidin, M.R.Z. (2016). Quality Assessment of Harvested Rainwater From Green Roofs Under Tropical Climate. *Desal. Water Treat.*, **57**(1), 75-82.

Sun, N.; Hall, M. (2016). Coupling Human Preferences with Biophysical Processes: Modeling the Effect of Citizen Attitudes on Potential Urban Stormwater Runoff. *Urban Ecosyst.*, **19**, 1433-1454.

Sun, Y.; Tong, S.; Yang, Y. J. (2016). Modeling the Cost-Effectiveness of Stormwater Best Management Practices in an Urban Watershed in Las Vegas Valley. *Appl. Geog.*, **76**, 49-61.

Taffere, G. R.; Beyene, A.; Vuai, S. A. H. (2016). Characterization of Atmospheric Bulk Deposition: Implications on the Quality of Rainwater Harvesting Systems in the Semi-Arid City of Medelle, Northern Ethiopia. *Environ. Process*, **3**(247), 247-261.

Tavakol-Davani, H.; Goharian, E.; Hansen, C. H.; Tavakol-Davani, H.; Apul, D.; Burian, S. J. (2016). How Does Climate Change Affect Combined Sewer Overflow in a System Benefiting From Rainwater

Harvesting Systems? *Sustain. Cities Soc.*, **27**, 430-438.

Tahsin, S.; Chang, N. (2016). Fast Eutrophication Assessment for Stormwater Wet Detention Ponds Via Fuzzy Probit Regression Analysis Under Uncertainty. *Environ. Monitor. Assess.*, **188**(2), 77.

Tang, S.; Luo, W.; Jia, Z.; Liu, W.; Li, S.; Wu, Y. (2016). Evaluating Retention Capacity of Infiltration Rain Gardens and Their Potential Effect on Urban Stormwater Management in the Sub-Humid Loess Region of China. *Water Resour. Manage.*, **30**(3), 983-1000.

Thompson, J.; Sattar, A. M.; Gharabaghi, B.; Warner, R. C. (2016). Event-Based Total Suspended Sediment Particle Size Distribution Model. *J. Hydrol.*, **536**, 236-246.

Tian, J.; Miller, V.; Chiu, P. C.; Maresca, J. A.; Guo, M.; Imhoff, P. T. (2016). Nutrient Release and Ammonium Sorption by Poultry Litter and Wood Biochars in Stormwater Treatment. *Sci. Total Environ.*, **553**, 596-606.

Toran, L. (2016). Water Level Loggers As a Low-Cost Tool for Monitoring of Stormwater Control Measures. *Water*, **8**(8), 1-10.

Trenouth, W. R.; Gharabaghi, B. (2016). Research Papers: Highway Runoff Quality Models for the Protection of Environmentally Sensitive Areas. *J. Hydrol.*, **542**, 143-155.

Turk, R. P.; Kraus, H. T.; Hunt, W. F.; Carmen, N. B.; Bilderback, T. E. (2016). Nutrient Sequestration by Vegetation in Bioretention Cells Receiving High Nutrient Loads. *J. Environ. Eng.*, **143**(2), 06016009.

Vacca, K.; Komlos, J.; Wadzuk, B. M. (2016). Phosphorus Removal in Constructed Stormwater Wetland Mesocosms Amended with Water Treatment Residuals. *Water Environ. Res.*, **88**(9), 898-906

Valdez, M. C.; Adler, I.; Barrett, M.; Ochoa, R.; Perez, A. (2016). the Water-Energy-Carbon Nexus: Optimizing Rainwater Harvesting in Mexico City. *Environ. Proces.* **3**(2), 307-323.

Vietz, G. J.; Rutherfurd, I. D.; Fletcher, T. D.; Walsh, C. J. (2016). Thinking Outside the Channel: Challenges and Opportunities for Protection and Restoration of Stream Morphology in Urbanizing Catchments. *Landscape Urban Plan.*, **145**, 34-44.

Vijayaraghavan, K.; Praveen, R. S. (2016). Dracaena Marginata Biofilter: Design of Growth Substrate and Treatment of Stormwater Runoff. *Environmental Technol.* **37**(9), 1101-1109.

Vogel, J. R.; Moore, T. L. (2016). Urban Stormwater Characterization, Control, and Treatment. *Water Environ. Res.* **88**(10), 1918-1950.

Vymazal, J.; Březinová, T. (2016). Accumulation of Heavy Metals in Aboveground Biomass of *Phragmites Australis* in Horizontal Flow Constructed Wetlands for Wastewater Treatment: A Review. *Chem. Eng. J.*, **290**, 232-242

Walsh, C. J.; Fletcher, T. D.; Vietz, G. J. (2016) Variability in Stream Ecosystem Response To Urbanization: Unraveling the Influences of Physiography and

Urban Land and Water Management. *Prog. Phys. Geog.*, **40**(5), 714-731.

Wang, G.; Feng, W.; Zeng, X.; Wang, Z.; Feng, C.; Mccarthy, D. T.; Zhang, X. (2016). Highly Recoverable Tio2–Go Nanocomposites for Stormwater Disinfection. *Water Res.*, **94**, 363-370.

Wang, J., Zhang, P., Yang, L.; Huang, T. (2016). Cadmium Removal From Urban Stormwater Runoff Via Bioretention Technology and Effluent Risk Assessment for Discharge To Surface Water. *J. Water Environ. Res. Contam. Hydrol.*, **185-186**, 42-50.

Wang, M., Zhang, D., Adhityan, A., Ng, W. J., Dong, J., & Tan, S. K. (2016). Assessing Cost-Effectiveness of Bioretention on Stormwater in Response To Climate Change and Urbanization for Future Scenarios. *J. Hydrol.*, **543**, 423-432.

Ward, E. W.; Winter, K. (2016). Missing the Link: Urban Stormwater Quality and Resident Behaviour. *Water SA*, **42**(4), 571-576.

Wella-Hewage, C. S.; Hewa, G. A.; Pezzaniti, D. (2016). Can Water Sensitive Urban Design Systems Help To Preserve Natural Channel-Forming Flow Regimes in an Urbanised Catchment? *Water Sci. Technol.*, **73**(1), 78-87.

Whittinghill, L. J.; Hsueh, D.; Culligan, P.; Plunz, R. (2016). Stormwater Performance of a Full Scale Rooftop Farm: Runoff Water Quality. *Ecol. Eng.*, **91**(6), 195-206.

Wijesiri, B.; Egodawatta, P.; Mcgree, J.; Goonetilleke, A. (2016a). Assessing Uncertainty in Stormwater Quality Modelling. *Water Res.*, **103**, 10-20.

Wijesiri, B.; Egodawatta, P.; McGree, J.; Goonetilleke, A. (2016b). Influence of Uncertainty Inherent To Heavy Metal Build-Up and Wash-Off on Stormwater Quality. *Water Res*., **91**, 264-276.

Winston, R. J., Al-Rubaei, A. M.; Blecken, G. T.; Hunt, W. F. (2016). A Simple Infiltration Test for Determination of Permeable Pavement Maintenance Needs. *J. Environ. Eng.*, **142**(10).

Winston, R.J.; Al-Rubaei, A.M.; Blecken, G.T.; Viklander, M.; Hunt, W.F. (2016). Maintenance Measures for Preservation and Recovery of Permeable Pavement Surface Infiltration Rate – The Effects of Street Sweeping, Vacuum Cleaning, High Pressure Washing, and Milling. *J. Environ. Manage.*, ***169***, 132-144.

Winston, R.J.; Davidson-Bennett, K.M.; Buccier, K.M.; Hunt, W.F. (2016). Seasonal Variability in Stormwater Quality Treatment of Permeable Pavements Situated Over Heavy Clay and in a Cold Climate. *Water Air Soil Pollut.* **227**(140).

Winston, R. J.; Dorsey, J. D.; Hunt, W. F. (2016). Quantifying Volume Reduction and Peak Flow Mitigation for Three Bioretention Cells in Clay Soils in Northeast Ohio. *Sci. Total Environ.*, **553**, 83-95.

Wright, T. J.; Liu, Y.; Carroll, N. J.; Ahiablame, L. M.; Engel, B. A. (2016). Retrofitting LID Practices

Into Existing Neighborhoods: Is it Worth it? *Environ. Manage.*, **57**(4), 856-867.

Wu, M.; Lin, C.; Huang, W.; Chen, J. (2016). Characteristics of Pervious Concrete Using Incineration Bottom Ash in Place of Sandstone Graded Material. *Constr. Build. Mater.* **111**, 618-624.

Xu, J.; Lo, S. L.; Xu, L. (2016). Removal of Pollutants During Storm and Non-Storm Events by Two Wetlands. *Desal. Water Treat.,* **57**(22), 10391-10402.

Yan, Q.; Davis, A. P.; James, B. R. (2016). Enhanced Organic Phosphorus Sorption from Urban Stormwater Using Modified Bioretention Media: Batch Studies. *J. Environ. Eng.*, **142**(4), 4016001-1-4016001-11.

Zaremba, G. J.; Traver, R. G.; Wadzuk, B. M. (2016). Impact of Drainage on Green Roof Evapotranspiration. *J. Irrig. Drain. Eng.*, **142**(7).

Zellner, M.; Massey, D.; Minor, E.; Gonzalez-Meler, M. (2016) Exploring the Effects of Green Infrastructure Placement on Neighborhood-Level Flooding Via Spatially Explicit Simulations. *Comput., Environ. Urban Syst.,* **59**, 116-128.

Zhang, K.; Che, W.; Zhang, W.; Zhao, Y. (2016). Discussion About Initial Runoff and Volume Capture Ratio of Annual Rainfall. *Water Sci. Technol.* **74**(8), 1764-1772.

Zhang, K.; Randelovic, A.; Deletic, A.; Page, D.; McCarthy, D. T. (2016). Stormwater Biofilters: A New Validation Modelling Tool. *Ecol. Eng.*, **87**, 53-61.

Zhang, K.; Valognes, V.; Page, D.; Deletic, A.; McCarthy, D. (2016). Validation of Stormwater Biofilters Using in-Situ Columns. *Sci. Total Environ.,* **544**, 48-55.

Zhou, Z.; Xu, P.; Cao, X.; Zhou, Y.; Song, C. (2016). Efficiency Promotion and its Mechanisms of Simultaneous Nitrogen and Phosphorus Removal in Stormwater Biofilters. *Bioresour. Technol.*, **218**, 842-849.