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Co-Design of Engineered Hyporheic Zones to Improve In-Stream Stormwater Treatment and Facilitate Regulatory Approval

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Abstract: Green infrastructure is an increasingly popular approach to mitigate widespread degradation of urban waters from stormwater pollution. However, many stormwater best management practices (BMPs) have inconsistent water quality performance and are limited to on-site, land-based deployments. To address basin-wide pollutant loads still reaching urban streams, hyporheic zone engineering has been proposed as an in-stream treatment strategy. Recognizing that regulator and practitioner perspectives are essential for innovation in the water sector, we interviewed U.S. water management professionals about the perceived risks, opportunities, and knowledge gaps related to in-stream stormwater treatment. We used engineered hyporheic zones as a case study to understand interviewee perspectives on an emerging class of in-stream treatment technologies. Interviews revealed that many considerations for in-stream stormwater treatment are common to land-based BMPs, but in-stream BMPs have additional unique design and siting requirements. Here, we synthesize practitioner goals, their recommendations on in-stream BMP design, and open research questions related to in-stream BMPs. Many interviewees suggested pairing engineered hyporheic zones with other BMPs in a treatment train to improve in-stream treatment, while simultaneously reducing risk and cost. We discuss how treatment trains and other strategies might also help overcome regulatory hurdles for innovative stormwater treatment.

Keywords: stormwater; low impact development; green infrastructure; urban hydrology; nonpoint source pollution; in-stream treatment; hyporheic; co-design

1. Introduction

Urban nonpoint source pollution is the fastest-growing cause of surface water quality impairment in the U.S. [1], and urban streams around the world face similar degradation [2]. Land-based best management practices (BMPs, also known as stormwater control measures or sustainable drainage systems), such as bioretention and grass swales, can remove contaminants and reduce peak storm flows [3–6]. However, stormwater can still reach the urban stream corridor by draining from lands with insufficient BMP coverage or by passing untreated through undersized and/or unmaintained BMPs [7–9]. In some locations, expanding BMP coverage may still be an insufficient strategy to address stream impairments. For example, all nonpoint source violations in Los Angeles, California would not be eliminated even if all available public land were retrofitted with typical green infrastructure BMPs [10]. To mitigate widespread impairments of urban streams and downstream habitats [1,11,12], many studies have called for a comprehensive management approach in which in-stream strategies (e.g., stream restoration) are used to complement land-based stormwater BMPs [8,13–21].

Urban drainage channels range from natural streams to artificial gutters. Classification of these drainage channels as nature versus infrastructure is imprecise because of widespread human impacts on the environment and the incorporation of natural processes into engineered green infrastructure designs [22]. For simplicity, the term "in-stream" is used for all channels along the artificial-natural continuum, but regulatory distinctions are discussed in detail later in this paper. In-stream treatments can address untreated and undertreated stormwater by enhancing the contaminant attenuation capacity of urban drainage channels at a semi-centralized scale. Unfortunately, few stormwater BMPs (i.e., detention ponds, wetlands) are designed for in-stream use, and only wetland channels do so in a confined urban stream footprint [3]. As with most stormwater BMPs, wetland channels can provide significant water quality benefits with respect to suspended solids and sediment-bound metals, but generally do not treat dissolved metals or bacteria, can actually act as net sources of nutrients, and have limited performance data for the dozens of organic contaminants that are consistently detected in urban stormwater [3,23–25].

Efforts to improve contaminant removal in-stream could better incorporate the hyporheic zone (HZ), which has been referred to as a river's liver due to its unique role as a natural biofilter [26]. Located in streambed sediments at the interface of surface water and groundwater, the HZ is known to attenuate a variety of stormwater and wastewater contaminants found in urban streams [27–31]. However, urban HZs are often scoured and clogged by hydromodification that limits their contributions to water quality [32], and there are no widely adopted stormwater BMPs that explicitly harness the HZ. To our knowledge, the only possible exception is a new treatment train technique called Regenerative Stormwater Conveyance (RSC), which uses a series of step-pools and subsurface geomedia to detain and treat stormwater, e.g., [33]. Experimental RSC systems show promise in restoring pre-development hydrographs and attenuating some contaminants [34,35], but do not yet prescribe specific hydraulic residence times to optimize contaminant removal. As a result, RSC systems can, at times, fail to reduce nitrate concentrations and be inactivated by groundwater upwelling [33].

To improve hyporheic circulation and target specific hyporheic residence times in urban channels, Herzog et al. [36] proposed a new HZ engineering technique called Biohydrochemical Enhancements for Streamwater Treatment (BEST). The BEST technique is based on the role of variations in sediment permeability in driving hyporheic exchange [37,38]. For example, consider a degraded urban stream with polluted surface water and a sandy streambed. The bedforms and meanders that normally mix surface water and streambed water are less common than in healthy streams, so almost all the surface water bypasses hyporheic treatment. Likewise, the streambed porewater may be treated thoroughly, but does not return to the stream efficiently after pollutant removal. A low-permeability baffle wall in the streambed can improve circulation by forcing clean water out of the hyporheic zone and bringing new, polluted surface water into the streambed for treatment.

BEST implementations use such baffle walls and geomedia emplaced in the streambed to increase hyporheic exchange, control residence times, and accelerate contaminant attenuation rates (Figures 1 and 2). A single BEST module is defined as the streambed sediment between two baffle walls; the number of modules in series can be selected to treat the desired fraction of total stream flow. Numerical models provided proof of principle [36], and flume experiments demonstrated proof of concept: BEST increased hyporheic exchange and reactive solute attenuation by 50% compared to a control [39]. BEST could be a standalone or complementary technique to increase the efficiency of RSC or other stormwater systems.

However, adoption of new technologies and approaches is notoriously slow in the water sector [40], in large part because inventors focus predominantly on technical solutions at the expense of feasibility and regulatory concerns. Therefore, it is unclear how BEST and related in-stream technologies can bridge the so-called "valley of death" [41] between invention and implementation, particularly when they do not fit into the dominant regulatory paradigm (e.g., in-stream versus land-based stormwater BMPs, stormwater treatment versus stream restoration). To improve technologies that address pressing issues in stormwater treatment, it is critical to coordinate innovations with the regulators and practitioners that approve, design, and implement stormwater BMPs [42].

This study reports on our efforts to identify the potential opportunities and limitations of in-stream stormwater BMPs through interviews with stormwater regulators and practitioners. In this study, we synthesize practitioner input to identify both technical and nontechnical design challenges and open research questions related to in-stream stormwater treatment. Next, we discuss the main results of our surveys with respect to implementation of enhanced in-stream technologies – centered on siting issues and the advantage of tying new technologies into existing practices to improve treatment performance and facilitate regulatory approval.

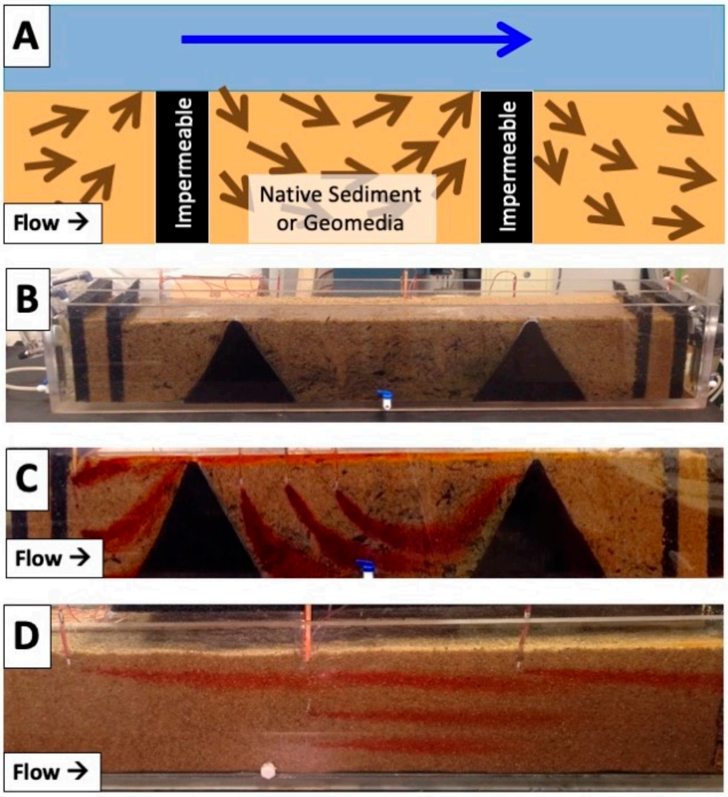

Figure 1. (**A**) Conceptual diagram of flow in and out of the BEST module, (**B**) BEST tank with two impermeable triangles installed and sand/woodchip geomedia mix, and (**C**) red dye showing BEST creating hyporheic exchange compared to (**D**) control tank with no exchange. Each tank measures 178 cm long, 28 cm deep, and 13 cm wide (text and caption exactly as shown to the interviewees upon request).

Figure 2. Photos from constructed streams showing (**A**) triangular BEST modules and sand/woodchip geomedia in BEST stream (right) versus all-sand control stream (left), and (**B**) BEST and Control streams running side by side at 0.5 L/s (0.02 cfs). Each stream measures 15 m long, 0.3 m deep, and 0.35 m wide (text and caption exactly as shown to the interviewees upon request).

2. Methods

2.1. Interviews

We conducted 13 telephone interviews with 19 stormwater professionals in California and Colorado in July and August of 2016 (in some instances, multiple professionals were questioned as part of the same phone interview). These two states encompass a range of stormwater management conditions, with wide variation in rainfall patterns, annual temperature, slope, stormwater contaminants of concern, and development conditions. The interviewees were selected to span a range of stormwater management roles, including municipal and agency engineers (five), municipal and agency planners (three), consulting engineers (three), landscape architects (three), real estate developers (two), public works officials (one), and policy professionals (two). In addition, interviewees were selected to represent a range of implementation contexts, including municipalities of varying sizes, varying climate types within California and Colorado, agencies with different water management scopes (stormwater only versus combinations of stormwater, wastewater and water supply), and agencies managing varying types of relevant water infrastructure (green infrastructure, combined sewers, and recycled water). In selecting interviewees, extensive direct experience with stormwater project management and BMPs was prioritized over seniority within the agency or firm in question. Therefore, the individuals interviewed from public sector agencies were managers or directors of stormwater infrastructure implementation or maintenance programs, but generally not in the senior leadership of the agency, while those from the private sector were consultants or project managers specializing in stormwater projects.

We used a semi-structured interview methodology, e.g., [43,44] that followed a scripted set of questions (see Appendix A) but expanded upon these questions when the interviewer identified a unique perspective or wanted to gain a clearer understanding of a specific topic that was discussed. The scripted questions focused on desirable performance specifications, system dimensions, seasonal variability and peak flows, highest-priority stormwater pollutants, desirable visual and aesthetic characteristics, desirable construction and maintenance characteristics, cost targets, important regulatory gatekeepers, and foreseeable regulatory challenges for BEST systems. The express intent of the interviews was to gather input on these topics from experienced stormwater professionals during—as opposed to after—the technical research and development of in-stream stormwater treatment systems, so that these technologies may be optimized to meet the practical needs of working stormwater engineers, designers, and planners in real-world implementation contexts. Interviews were not audio recorded. Responses represent the interviewer's notes taken during the interviews. Quotes reflect a faithful attempt to capture interviewee's verbatim responses. All responses were considered in the formulation of the research results reported here, but not all responses were directly quoted.

2.2. Interpretation

The goal of these interviews was to capture a wide range of feedback rather than to determine majority or plurality opinions, and all relevant practitioner feedback is reported. Responses were grouped by thematic coding for clarity. Many responses could reasonably be assigned to multiple categories, but such distinctions were insignificant because they only dictated where, as opposed to if, each result was reported. To place our findings in a broader context, we draw on additional literature examples from around the U.S. and other countries. While effort is made to provide the necessary regulatory context for U.S. water management, an exhaustive review of numerous diverse and hierarchical stormwater and stream restoration regulations is beyond the scope of this research.

3. Results

We present summary responses grouped into three overarching questions, as shown below.

3.1. What Are the Stakeholder Concerns Related to Novel In-Stream Stormwater Treatment Technologies?

3.1.1. The Need to Reliably Meet Diverse Water Quality Control Standards

Water quality is defined differently by various respondents: standards can be volume-based, concentration-based, or load-based depending on local regulations. Such variety is not unique to the United States, as the European Union member states and other countries also feature a mixture of flow-based, volume-based, and concentration-based stormwater standards [45]. For example, some respondents would judge a new technology by its ability to achieve 80% total suspended solids removal during field trials (i.e., concentration-based), while others consider an assumed level of total suspended solids removal indirectly through an established detention time for a design storm (i.e., volume-based). Stakeholders suggest that an ideal technology would thus be able to meet all types of standards consistently and predictably, including in dry or cold seasons. Practitioners subject to concentration-based standards noted that dissolved contaminants are more difficult to treat than suspended solids and sediment-bound contaminants. Furthermore, a wide range of dissolved contaminants are frequently named as key pollutants of concern, including *Escherichia coli* and other fecal indicator bacteria, nutrients, and metals. Other respondents were less concerned with "removal efficiencies at each [treatment] stage" (i.e., percent removal) and more focused on "the bottom line" of getting below a threshold pollutant concentration at the end of treatment.

3.1.2. Cost and Space Demands

Several respondents noted the success of bioretention technologies as a de facto competitive standard (i.e., "the default that everyone accepts") for new technologies to match. Justification was based on bioretention's relatively low cost and small spatial footprint to achieve compliance. Some expressed concern about the potential need for expensive liners in BEST, while others noted that liner costs could be justified by performance. Most interviewees emphasized the importance of considering long-term operational costs at least as strongly as capital and installation costs.

3.1.3. Risk of Catastrophic Failure

Two interviewees discussed a general lack of confidence that any particular BMPs will work consistently. One said that "We end up using a shotgun approach because we don't know a lot about BMP performance", while another noted that they have "seen a lot of cases where the same BMP succeeds in one place and fails in another and it's not clear why." In particular, one respondent cited "total failure" of previous flow-through stormwater treatment technologies due to clogging. Clogging is a major potential concern for engineered HZs, and can be especially common in areas where stormwater carries high sediment loads.

3.1.4. Stormwater Treatment Must Occur Before Reaching Receiving Waters

A critical issue with respect to in-stream technologies is whether they are intended for placement in receiving waters, which in the U.S. are called waters of the state or waters of the U.S. (WOTUS). In brief, waters of the state automatically include all WOTUS that are located within a given state, but some states have more expansive definitions that also include additional streams. For brevity, we use the term "jurisdictional waters" to represent both waters of the state and WOTUS. One respondent said that "treatment before it reaches [jurisdictional waters] is key" because outfalls to receiving waters are typically the point of stormwater compliance. Furthermore, water treatment within jurisdictional waters is discouraged by the Clean Water Act except in extreme circumstances [46]. Accordingly, some respondents felt that regulatory approval for treatment in jurisdictional waters may not be worth pursuing: "Once you put a structure in (jurisdictional waters), the regulators have problems. Would be very hard to permit that."

3.1.5. Acceptance by Regulatory Gatekeepers

Many respondents stated that "regulators need to accept something" or it becomes more difficult to convince agencies, developers, or elected officials to approve a technology's use. According to one interviewee, "It's not as much consultants recommending [a BMP] as it is municipalities accepting it. It has to fit within the regulatory requirements." The International Stormwater BMP Database, the Washington Department of Ecology, and the New Jersey Corporation for Advanced Technology were all cited as influential regulatory gatekeepers, along with regional and state water quality regulators. These results align with literature showing that in most countries, local stormwater agencies simply adopt regional or national stormwater guidelines [45]. One larger municipal stormwater agency expressed willingness to pioneer new and improved technologies without waiting for blanket regulatory approval (i.e., inclusion in a widely used stormwater BMP manual), and others echoed this sentiment when they need to meet concentration or load limits at specific sites. However, most respondents stated that it is simpler to select a pre-approved BMP. Representative quotes include: "Just take a look at the manual and see if you can mimic that", "We would only go beyond the norm in special circumstances", and "There are no specific targets so it's more about complying with [the regulatory agency's] needs. There are a rare few who would pay more to do the right thing, but not most."

3.2. What Technical and Nontechnical Design Modifications Could Improve Acceptance and Feasibility of In-Stream BMPs?

3.2.1. Treatment Trains and Hardscape Elements for Scalability Across a Range of Discharges

Many respondents thought BEST and other in-stream treatments would benefit greatly from a treatment train approach in which they are paired with other complementary BMPs. For example, interviewees recommended siting BEST downstream of a flow attenuation BMP (e.g., detention ponds) and including hardscape elements to minimize the risk of scouring "blow-outs". Notably, hardscape can be made from natural materials such as logs and boulders to maintain a natural aesthetic. Others suggested that coupling BMPs like BEST with detention basins, settling forebays, or another pre-treatment BMPs would also allow trash and sediment to settle out of stormwater and reduce clogging of the streambed. Some practitioners also questioned whether the engineered HZ would be able to treat a significant fraction of the total stormwater discharge during peak flows and wanted to see performance data at field scale. It was also noted that in-channel BMPs like BEST, unlike many land-based BMPs, would be beneficial to use for treating dry weather flows. Dry weather flows tend to have low but consistent discharge with high concentrations of contaminants. One respondent noted that dry-weather flows are harder to manage because water quality standards are more stringent for dry-weather flows than water quality standards for wet-weather flows. Therefore, BEST performance in removing pollutants from these dry-weather flows may be as important as wet-weather performance.

3.2.2. Design for Ease of Maintenance

Almost all respondents cited ease of maintenance as a critical concern, with one stating that "maintenance is probably even more important than pollutant removal efficiencies" as a technology selection criterion. The interviewee added, "some BMPs we will never use again because of maintenance struggles." Cited factors affecting ease of maintenance include ease of geomedia replacement, avoidance of woody vegetation that might impede geomedia clean-out, avoidance of confined space entry, ease of maintenance truck or vacuum truck access, use of standard sizes and shapes to facilitate use of skid-loader buckets and other standard-sized equipment, and the frequency of anticipated maintenance. One interviewee explained that the average BMP requires 60 hours of maintenance per year. Another respondent cited a geomedia replacement frequency of once per 8–10 years as "tolerable," but any higher frequency as problematic. One respondent asked if geomedia could be placed inside a cartridge "so that it can be drop-in-place? That would be nice." In addition, multiple respondents indicated that BMPs should be designed for maintenance by crews without any technical expertise on their operation.

3.2.3. Focus on Retrofits for Cost-Effectiveness

Several interviewees suggested that in-stream treatments could be attractive as retrofits. "Right now less than 20–30% of the watershed area is getting water quality treatment, so there is tons of retrofit opportunity." One described the lack of available land within the urban growth boundary and liked that in-stream BMPs are not "consuming any additional land if [they] can fit between the outlet structure and the receiving water." Another noted that peak flow is already addressed by other BMPs, so semi-centralized in-stream retrofits could focus on water quality treatment.

3.2.4. Maximize Aesthetics, Recreation, and Property Values

Most respondents identified aesthetic appearance as a critical factor in the acceptance of new stormwater technologies by developers and the general public, especially in predominantly residential environments. In general, respondents judged a "naturalistic look, not too mowed or manicured" as the most favored, potentially including meanders or "wet meadow" plants such as sedges, rushes, and certain grasses. Consideration should also be given to how the aesthetics of the technology change in dry or cold seasons, and avoidance of trash accumulation and bad odors. In locations with high property values, it can be much more cost-effective to treat stormwater within the existing channel footprint rather than allocating buildable space for land-based BMPs. Real estate developers described how stormwater features with a natural aesthetic are very popular for walking trails, such that investing in ponds, wetlands, and in-stream treatments can justify higher costs by increasing property values, as long as such systems are properly maintained. These responses align closely with a stormwater project in Durham, North Carolina, where 76–91% of stakeholders surveyed considered trails, boardwalks, seating, and educational signage to be "important parts of any new stormwater management design" [47].

3.3. What Knowledge Gaps Remain for In-Stream BMPs That Impact Practitioner Acceptance?

3.3.1. Performance in Effluent Concentration, not Percent Pollutant Removal

Because in-stream BMPs would function within an urban drainage network as opposed to an individual urban site, they would likely receive inflows with mixed pollutant loads that vary geographically and seasonally, both in composition and in concentration (or mass load). As a result, reliable achievement of performance targets in effluent concentrations may be more valuable than reliable achievement of pollutant removal percentages. Regardless of how removal is assessed, specific contaminants of concern varied. One respondent identified potential removal of *Escherichia coli*, in particular, as the "holy grail" of urban stormwater treatment. Several others stated that any BMP that could be shown to remove *Escherichia coli* predictably, reliably, and affordably would find widespread applicability. Others said that they are looking for a single BMP that can effectively treat multiple contaminant classes (i.e., nutrients, metals, and pesticides) to comply with specific load reduction targets.

3.3.2. How Do In-stream BMPs Handle Cold Season Challenges?

When asked about seasonal changes in performance, several practitioners mentioned freeze-thaw cycles but noted that freezing has not been a concern at any of their field sites. One Colorado interviewee said of freeze-thaw, "we don't seem to have that problem here—we usually have several thaws throughout winter, so water can continue to infiltrate". Two interviewees described that water quality standards do not change in winter, with one adding that "it would be really valuable to have data on seasonal differences" in biological performance of BEST. One noted that concentrations of bacteria in stormwater are much lower during winter, but several also mentioned the potential for high-concentration slugs of de-icing salts to reach in-stream BMPs in the winter in cold climates, potentially harming fish and killing BMP vegetation. Better understanding of seasonal performance and the resilience of an in-stream BMP to freezing and salt pulses is needed in cold climates.

3.3.3. Life-cycle Costs

As with any new stormwater technology, the importance of a field-scale performance record cannot be overstated. Interviewees expressed a need to accurately estimate the costs of capital and installation as well as ongoing operation and maintenance. Several respondents also factor in the cost of land, the cost of sending stormwater to combined sewers, or the "triple bottom line" of financial, social, and environmental costs. Generally, interviewees noted that any new technology should be competitive with other green infrastructure BMPs, but some also said they would be willing to pay more for better performance.

3.3.4. Defining Jurisdictional Boundaries for Stormwater Management

Respondents told us that in-stream stormwater treatment is far simpler to approve upstream of any outfall to jurisdictional waters. Certain locations within an urban drainage or storm sewer network may be classified as jurisdictional by the US Army Corps of Engineers—a designation that can also vary through time—and thus be subject to much greater regulatory scrutiny. Further clarification of the potential regulatory limitations this might place on deployment of stormwater technologies within jurisdictional waters would be needed as stormwater regulations evolve.

4. Discussion

A participatory design approach was used to collect stakeholder feedback about in-stream stormwater treatment BMPs. Our interviews showcased how new approaches and BMPs can present a diverse set of challenges and opportunities for the stormwater community. However, any discussion of the topics and concerns raised by respondents should also include prior analyses from stormwater literature from many other climatic and regulatory settings alongside design advice from the interviewees and the authors (Table 1). Although centered on in-stream BMPs, many of the interview results are also relevant for land-based BMPs. In fact, all topics raised by interviewees for in-stream BMPs have been explored by at least one other study in the context of land-based BMPs or Low Impact Development generally (Table 1, columns 1 and 2). For example, the need for better performance and cost data are common themes for all stormwater BMPs. In contrast, the topics of design advice, knowledge gaps related to design, risk management, and jurisdictional considerations have not been addressed as extensively in the literature. Accordingly, we focus our discussion on these previously underemphasized topics, which are especially prominent for in-stream treatment.

Table 1. For each topic raised by interviewees regarding in-stream BMPs (e.g., BEST), we present related findings from studies of land-based BMPs (e.g., bioretention) and relevant design advice from interviewees and authors for in-stream BMPs.

Topic Raised by Interviewees for In-Stream BMPs	Studies with Similar Findings for Land-Based BMPs/Low Impact Development (LID)	Design Advice from Interviews (I) and Authors (A) for In-Stream BMPs
Need to meet different types of standards (e.g., volume-based, load-based) depending on local regulations.	Sage et al. [42] and Vogel et al. [48] compare many different types of standards and their impacts on stormwater BMP implementation.	I: Pair with other BMPs in a treatment train to meet water quantity and quality regulations.
For concentration- and load-based standards, need to manage diverse contaminant(s) of interest depending on local regulations.	Vogel et al. [48] discuss geomedia mixes and BMP design modifications to target specific pollutants; Wolfand et al. [49] show geomedia can improve water quality compliance for load- and concentration-based standards.	A: Include multiple types of geomedia to address multiple contaminant classes.
Need to perform consistently across sites and seasons.	Moore et al. [45] highlight the need to understand how BMP designs influence performance; Roseen et al. [50] showed modest declines in winter performance for most BMPs; Blecken et al. [51] recommend conservative crediting and design factors of safety to account for uncertainty.	A: Conduct mechanistic studies of water quality performance to improve design; use a factor of safety to account for slower biological treatment in cold seasons.
Need to perform at scale (i.e., treat higher flow rates).	Olorunkiya et al. [52] discuss risk factors (e.g., limited design examples and fear of liability) as barriers to LID implementation; these factors are reduced by demonstration projects.	I: Pair with flow modulation BMPs; focus on polishing effluents and dry-weather flows.
Need for resilience to freezing and high salt	Roseen et al. [50] found that frost penetration had a negligible impact on	A: Ensure resilience of BMPs to pulses of road

loads in winter.	most BMPs performance; Snodgrass et al. [53] conclude that green infrastructure BMPs cannot treat road salts and instead advocate for source controls.	salts, such as avoiding geomedia that sorb via cation exchange.
Costs (capital and operational) should be competitive with alternative options.	Houle et al. [54] compared fixed and ongoing costs of BMPs, and found that LID systems generally have greater water quality performance than conventional systems at lower costs.	I: Design for ease of maintenance; include sedimentation forebay or pre-treatment.
Minimize maintenance, especially geomedia replacement interval and effort.	Ashoori et al. [55] found that additions of biochar geomedia can improve water quality performance without increasing media replacement intervals.	I: Use cartridges for easy geomedia replacement and select geomedia with appropriate lifespans.
Minimize land footprint.	Nobles et al. [56] show that seemingly cost-effective BMPs can actually be non-economical after considering the cost of land footprint.	I: Retrofit existing stormwater channels.
Uncertain cost-benefit compared to other green and gray infrastructure BMPs.	Roy et al. [47] and Barbosa et al. [57] discuss uncertainties in performance and cost as major barriers to stormwater BMP use; Bell et al. [46] show the same cost-benefit uncertainty across the green-gray continuum.	I: Monitor performance and costs at scale, not just in lab-scale or pilot-scale flumes.
Minimize risk of catastrophic failure (e.g., clogging, blowout).	Hatt et al. [58] suggest that one high profile failure can permanently undermine a novel stormwater approach.	I: Use treatment train for upstream flow and sediment control; hardscape elements to prevent scour.
Need for acceptance by regulatory gatekeepers.	Lane et al. [59] use Australian case studies to show that regulatory framework influences the workflow and ease of approving novel stormwater approaches.	A: Co-design with regulators and practitioners; pursue inclusion in stormwater guidance manuals.
Difficulty permitting stormwater structures in jurisdictional waters.	The Chesapeake Bay expert panel on stormwater retrofits removed an in-stream BMP category from consideration, noting that it "appeared to show a retrofit in waters of the US and would not be allowed under state or federal wetland permits" [60].	I: Avoid applications in jurisdictional waters.
Opportunity for in-stream BMPs to provide or	BenDor et al. [44] discuss stormwater BMPs as "artistic features" and the	A: Emphasize integration with

complement recreation (e.g., trails).	broader ecosystem services of green infrastructure in addition to water quantity and quality.	community amenities and recreation (e.g., walking trails).
Opportunity for in-stream BMPs to improve aesthetics, which in turn may boost property values.	Hansen et al. [61] report many LID projects contributing to recreation, habitat, and urban revitalization in Europe; Wolch et al. [62] present similar findings from the U.S. and China but warn that rising property values can cause gentrification and displace residents.	I: Prioritize natural aesthetics; A: Add features that help improve ecosystem health (e.g. biodiversity).

4.1. Design Advice from Interviewees

Interviewees gave specific design advice to help in-stream BMPs deliver consistent and predictable water quality treatment while minimizing costs and risks (Section 3.3; Table 1). Based on this feedback, the best candidates for in-stream treatment are stormwater channels draining detention ponds and other flow-regulating BMPs, as well as channels that have dry weather flow. Detention pond effluent channels already receive modulated flows and pre-sedimentation, and can be retrofitted within the existing footprint to provide better water quality. Detention features usually release stored stormwater slowly over 12–72 h; thus, placing in-stream treatment downstream of a detention basin outlet would have the additional benefit of lowering the dosing rate and improving the fraction of total water treated per BEST module. Furthermore, water quality retrofits are expected to be relatively cost-effective and easy to permit compared to brand new facilities. Future designs for BEST and other in-stream BMPs should also include hardscape elements to prevent scour, and geomedia cartridges or other time-saving techniques to minimize maintenance. Detention pond effluent channels can also be meandered and vegetated for natural aesthetic, and maintenance access roads can double as walking or biking trails for the community.

4.2. Research Knowledge Gaps Related to Design

All the performance data from BEST published thus far have been collected from controlled pilot-scale systems or were estimated based on modeling efforts. Some of the interviewees were concerned with scalability, revealing a need for performance data at field scale—both for storm flows and dry-weather flows. Performance data across seasons are also needed, especially for the biological component of treatment, as changes in temperature would affect microbially driven processes. Furthermore, seasonal performance data need to include resilience of the in-stream system to freeze-thaw cycles and occasional salt pulses. Other research topics to include are resistance to scour, changes in hydraulic conductivity from biofilm formation or clogging from sediment deposition, removal of contaminants not previously tested (*Escherichia coli*, deicers, metals, etc.), and long-term structural integrity. Additionally, construction and maintenance cost data will be necessary to compare the performance of BEST to its life cycle costs.

An emerging area of research is the use of engineered geomedia (e.g., biochar, polymerized clays) to sorb contaminants or promote the growth of beneficial bacteria. It is essential to research low-cost and nonproprietary geomedia mixes to efficiently remove a variety of stormwater pollutants simultaneously. Due to a wide range of mechanisms governing removal of each class of contaminants (and sometimes even within a class, e.g., in the case of metals), a better understanding of individual and mixed removal processes is needed. As described by Moore et al. [63], poor mechanistic understanding of water quality performance (including seasonal and operational variability) across many land-based BMPs prevents design optimization and customization. Improved process-based monitoring will allow the development of water quality specific design guidance for in-stream stormwater treatment systems. Methods to integrate engineered geomedia into BEST will also need to be studied. For instance, it is not known if engineered geomedia need to be evenly mixed throughout the existing hyporheic sediments or if they can be added in specific locations, which may be feasible through the use of cartridges.

The authors also envision BEST as a complementary modification to existing infrastructure, such as bank stabilization structures, RSC, wetland channels, or bioswales. More research is needed, however, on the appropriate scaling and siting of in-stream BMPs in treatment train settings or when stormwater treatment optimization is investigated from an urban watershed-scale perspective.

4.3. Tradeoffs in Risk and Reward for Inventors and Regulators

Inventors from industry and academia have incentives to promote their design improvements as novel technologies, as evidenced by the hundreds of proprietary stormwater technologies on the market. However, all new BMPs need detailed field performance data to be approved by regulators and accepted by practitioners. The same strict adherence to proven and pre-approved designs is found in both stormwater and the closely-related field of stream restoration [64] and is logical from a risk management perspective in which potential liabilities can be felt more strongly than the hypothetical benefits of a new technique [52,65]. This represents a chicken-and-egg conundrum, because a BMP cannot be constructed in the field without prior performance data, but field performance data cannot be collected without a pilot field site. Designing, approving, and constructing a new BMP can take several years. Subsequent performance monitoring for multiple contaminants across different seasons requires significant investments of time and funds, which can be substantial hurdles to innovation.

These barriers to entry raise an important point about branding a BMP design as a new technology versus an improved version of an existing technology. First, a new in-stream BMP could arguably be considered an enhanced version of an existing BMP. For example, the interviewees' suggestion to pair BEST with a detention pond could simply be considered an improved version of a detention pond, which may streamline the regulatory approval process or bypass it altogether. This would allow in-stream BMPs to be tested at scale and optimized more rapidly, but must be considered carefully as the loss of proprietary status may disincentivize innovation. Alternatively, a new technology may be promoted as such, but still paired with another common BMP(s) in a treatment train to reduce risk and facilitate pilot testing. In the same example as above, BEST could be installed downstream of a detention pond and considered a separate BMP or polishing step without seeking additional water quality credit beyond the standard for detention ponds alone. This would provide a pilot site for field performance data as the basis for future crediting while preserving the intellectual property of the inventors. The same strategy of small, low-risk experimental deployments has been suggested for stream restoration as a means for academics and practitioners to co-generate long term performance data and develop consensus on best practices [65]. Lastly, the pilot scale innovative technology could be installed in parallel to an existing stream/BMP and the effluent of the technology could be directed back to the influent of the existing stream/BMP similarly to how technologies are piloted at wastewater or drinking water treatment plants.

4.4. Where Is Stormwater Treatment Permitted to Occur?

Our interview responses emphasized that it would be very difficult to obtain regulatory approval for any in-stream stormwater BMP applications in jurisdictional waters. Instead, all stormwater treatment should occur on-site or in small drainage channels upstream of the point of compliance. However, this approach has failed to address the widespread stormwater pollution that still reaches receiving waters. Nearly half of all river and stream miles in the U.S. are in poor biological condition [1]. For context, approximately half of E.U. rivers also fail to achieve good biological or chemical status due in large part to diffuse pollution [66]. As BenDor et al. [47] describe U.S. stormwater regulations, "federal stormwater rules (33 USC § 1342) often specify very tightly defined spatial and temporal effects that can be considered when monitoring or regulating stormwater… federal rules, as a result, can eliminate the ability to holistically consider non-point source discharges…" However, stormwater treatment in jurisdictional waters has occasionally been approved in areas where on-site treatment is technically infeasible [67], and has also been listed as an auxiliary benefit of (but not primary motivation for) urban stream restoration projects [68]. Calls for distributed stormwater management to be considered as a stream restoration technique, e.g., [21,69] further emphasize the potential overlap between the two sectors. Future research should explore regulatory perspectives on the interface of in-stream stormwater treatment and urban stream restoration to improve integrated management of diffuse pollution.

5. Conclusions

Reversing the global trend of declining urban water quality is a monumental task, which demands a multipronged approach. Distributed BMPs are being improved with modifications such as reactive geomedia [23] and real-time hydraulic control [70]. Additionally, non-structural BMPs like street sweeping and source controls are also being employed to great effect, e.g., [71,72]. However, in-stream stormwater treatment remains an underutilized service. Extensive drainage networks in urban areas not only span the green-gray infrastructure continuum, but also challenge the utility of the infrastructure versus nature dichotomy. Resolving the impairment of urban waters will require integrated use of all available technologies: source controls, land-based BMPs, and in-stream BMPs. With improved in-stream BMPs, urban waterways could better protect themselves and downstream environments from nonpoint source pollution, without utilizing any additional land footprint. In this study, we worked with water management professionals to understand the unique opportunities and challenges arising from in-stream stormwater treatment. Our goal was to report a wide range of opinions rather than to determine majority or consensus views. It may not be realistic for future stormwater BMP designs to accommodate all the feedback presented here. However, for each topic raised by interviewees, there was at least one piece of design advice from the interviewees or authors. While much of the feedback applied to both in-stream and land-based BMPs, we also identified unique concerns and opportunities for in-stream BMPs. For example, there is potential low-hanging fruit in the use of in-stream BMPs for water quality retrofits downstream from existing flow modulation and sedimentation BMPs. By consulting stormwater regulators and practitioners early in the development of in-stream stormwater treatments, we hope that technical and nontechnical hurdles can be defined, shared, and contemplated by a diverse group of stakeholders. Notably, co-design does not end at the data collection phase. Stakeholders from professional, regulatory, and academic institutions all benefit from ongoing collaborations in developing, installing, monitoring, and reflecting upon in-stream BMPs. More broadly, the approach presented in this paper for a specific technology can serve as a general framework to enhance diffusion of other new and improved stormwater green infrastructure into practice.

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Appendix A

The scripted questions used in the interviews are presented below.

1. What performance specs do you think need to be met for the BEST technology to be something you would consider using in your professional work? This can relate to pollutant removal effectiveness, removal reliability, flows that can be handled, resilience to high flow events, physical stability of system, etc.
2. BEST systems, by themselves, don't do anything to manage or reduce peak flows. Do they need to be installed in concert with a BMP for management of peak discharges in order to be useful to you?
3. What are the highest priority stormwater pollutants, in your opinion, that the BEST systems should be designed to remove?
4. What visual or aesthetic characteristics are most important for the BEST technology to be deployed in public spaces like street right-of-ways, parking lots, or parks? Are there particular plant types or plant species that you think could or should be planted around the BEST systems to enhance visual appeal?
5. What construction or maintenance characteristics do you think need to be met for the BEST technology to be something you would consider using in your professional work? What other BMPs from your current portfolio would you like to compare to BEST?
6. Are there particular targets for the cost of a BEST system that you would want to see met? (This could be expressed in relation to the cost of other common BMPs, in relation to the cost of installing storm sewers, or any other way.)
7. How important to you is design guidance from regulators and/or local agencies when you make decisions about which stormwater management techniques to use (not whether to use them)? Would a BEST system need to be "blessed" by inclusion in such guidance for you to consider using one?
8. What lengths and widths of BEST systems are most manageable in the design contexts that you work with? Any upper or lower limits?
9. Can you foresee any challenges—either regulatory or physical—with building constructed channels such as a BEST system? They involve excavating shallow trenches and creating semi-permanent open channels where there were none before.

References

1. USEPA (U.S. Environmental Protection Agency). *National Rivers and Streams Assessment 2008–2009: A Collaborative Survey*; EPA/841/R-16/007; Office of Water and Office of Research and Development: Washington, DC, USA, **2016**; pp. 1–116.
2. Booth, D.B.; Roy, A.H.; Smith, B.; Capps, K.A. Global perspectives on the urban stream syndrome. *Freshw. Sci.* **2016**, *35*, 412–420.
3. Clary, J.; Jones, J.; Leisenring, M.; Hobson, P.; Strecker, E. *International Stormwater BMP Database 2016 Summary Statistics*; Water Environment & Reuse Foundation: Alexandria, VA, USA, **2017**.
4. Scarlett, R.D.; McMillan, S.K.; Bell, C.D.; Clinton, S.M.; Jefferson, A.J.; Rao, P.S.C. Influence of stormwater control measures on water quality at nested sites in a small suburban watershed. *Urban Water J.* **2019**, *15*, 1–12.
5. Hunt, W.F.; Jarrett, A.R.; Smith, J.T.; Sharkey, L.J. Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina. *J. Irrig. Drain. Eng.* **2006**, *132*, 600–608.
6. Bhaskar, A.S.; Hogan, D.M.; Archfield, S.A. Urban base flow with low impact development. *Hydrol. Process.* **2016**, *30*, 3156–3171.
7. Booth, D.B.; Jackson, C.R. Urbanization of Aquatic Systems: Degradation Thresholds, Stormwater Detection, And The Limits Of Mitigation. *J. Am. Water Resour. Assoc.* **1997**, *33*, 1077–1090.
8. Bernhardt, E.S.; Palmer, M.A. Restoring Streams in an Urbanizing World. *Freshw. Biol.* **2007**, *52*, 738–751.

9. Jefferson, A.J.; Bhaskar, A.S.; Hopkins, K.G.; Fanelli, R.; Avellaneda, P.M.; McMillan, S.K. Stormwater management network effectiveness and implications for urban watershed function: A critical review. *Hydrol. Process.* **2017**, *31*, 4056–4080.
10. Mika, K.; Hogue, T.; Pincetl, S.; Gallo, E.; Gold, M. *LA Sustainable Water Project: Dominguez Channel & Machado Lake Watersheds*. UCLA Institute of the Environment and Sustanbility: Los Angeles, CA, USA, 2017.
11. Richmond, E.K.; Rosi, E.J.; Walters, D.M.; Fick, J.; Hamilton, S.K.; Brodin, T.; Sundelin, A.; Grace, M.R. A diverse suite of pharmaceuticals contaminates stream and riparian food webs. *Nat. Commun.* **2018**, *9*, 4491.
12. He, L.-M. He, Z.-L. Water quality prediction of marine recreational beaches receiving watershed baseflow and stormwater runoff in southern California, USA. *Water Res.* **2008**, *42*, 2563–2573.
13. Lammers, R.W.; Bledsoe, B.P. What role does stream restoration play in nutrient management? *Crit. Rev. Environ. Sci. Technol.* **2017**, *47*, 335–371.
14. Richardson, C.J.; Flanagan, N.E.; Ho, M.; Pahl, J.W. Integrated stream and wetland restoration: A watershed approach to improved water quality on the landscape. *Ecol. Eng.* **2011**, *37*, 25–39.
15. Fletcher, T.D.; Andrieu, H.; Hamel, P. Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. *Adv. Water Resour.* **2013**, *51*, 261–279.
16. Craig, L.S.; Palmer, M.A.; Richardson, D.C.; Filoso, S.; Bernhardt, E.S.; Bledsoe, B.P.; Doyle, M.W.; Groffman, P.M.; Hassett, B.A.; Kaushal, S.S.; et al. Stream restoration strategies for reducing river nitrogen loads. *Front. Ecol. Environ.* **2008**, *6*, 529–538.
17. Kondolf, G.M.; Angermeier, P.L.; Cummins, K.; Dunne, T.; Healey, M.; Kimmerer, W.; Moyle, P.B.; Murphy, D.; Patten, D.; Railsback, S.; et al. Projecting Cumulative Benefits of Multiple River Restoration Projects: An Example from the Sacramento-San Joaquin River System in California. *Environ. Manag.* **2008**, *42*, 933–945.
18. Kroll, S.A.; Horwitz, R.J.; Keller, D.H.; Sweeney, B.W.; Jackson, J.K.; Perez, L.B. Large-scale protection and restoration programs aimed at protecting stream ecosystem integrity: The role of science-based goal-setting, monitoring, and data management. *Freshw. Sci.* **2019**, *38*, 23–39.
19. Stanford, B.; Zavaleta, E.; Millard-Ball, A. Where and why does restoration happen? Ecological and sociopolitical influences on stream restoration in coastal California. *Biol. Conserv.* **2018**, *221*, 219–227.
20. Lammers, R.W.; Dell, T.A.; Bledsoe, B.P. Integrating Stormwater Management and Stream Restoration Strategies for Greater Water Quality Benefits. *J. Environ. Qual.* **2019**, doi:10.2134/jeq2019.02.0084.
21. Vietz, G.J.; Rutherfurd, I.D.; Fletcher, T.D.; Walsh, C.J. Thinking outside the channel: Challenges and opportunities for protection and restoration of stream morphology in urbanizing catchments. *Landsc. Urban Plan.* **2016**, *145*, 34–44.
22. Chester, M.V.; Markolf, S.; Allenby, B. Infrastructure and the environment in the Anthropocene. *J. Ind. Ecol.* **2019**, 12848, doi:10.1111/jiec.12848.
23. Ulrich, B.A.; Vignola, M.; Edgehouse, K.; Werner, D.; Higgins, C.P. Organic Carbon Amendments for Enhanced Biological Attenuation of Trace Organic Contaminants in Biochar-Amended Stormwater Biofilters. *Environ. Sci. Technol.* **2017**, *51*, 9184–9193.
24. LeFevre, G.H.; Paus, K.H.; Natarajan, P.; Gulliver, J.S.; Novak, P.J.; Hozalski, R.M. Review of Dissolved Pollutants in Urban Storm Water and Their Removal and Fate in Bioretention Cells. *J. Environ. Eng.* **2015**, *141*, 04014050.
25. Masoner, J.R.; Kolpin, D.W.; Cozzarelli, I.M.; Barber, L.B.; Burden, D.S.; Foreman, W.T.; Forshay, K.J.; Furlong, E.T.; Groves, J.F.; Hladik, M.L.; et al. Urban Stormwater: An Overlooked Pathway of Extensive Mixed Contaminants to Surface and Groundwaters in the United States. *Environ. Sci. Technol.* **2019**, *53*, 17.
26. Fischer, H.; Kloep, F.; Wilzcek, S.; Pusch, M.T. A river's liver-Microbial processes within the hyporheic zone of a large lowland river. *Biogeochemistry* **2005**, *76*, 349–371.
27. Hester, E.T.; Gooseff, M.N. Moving beyond the banks: Hyporheic restoration is fundamental to restoring ecological services and functions of streams. *Environ. Sci. Technol.* **2010**, *44*, 1521–1525.
28. Lewandowski, J.; Putschew, A.; Schwesig, D.; Neumann, C.; Radke, M. Fate of organic micropollutants in the hyporheic zone of a eutrophic lowland stream: Results of a preliminary field study. *Sci. Total Environ.* **2011**, *409*, 1824–1835.
29. Palumbo-Roe, B.; Banks, V.J.; Bonsor, H.C.; Hamilton, E.M.; Watts, M.J. Limitations on the role of the hyporheic zone in chromium natural attenuation in a contaminated urban stream. *Appl. Geochem.* **2017**, *83*, 108–120.

30. Peter, K.T.; Herzog, S.; Tian, Z.; Wu, C.; McCray, J.E.; Lynch, K.; Kolodziej, E.P. Evaluating emerging organic contaminant removal in an engineered hyporheic zone using high resolution mass spectrometry. *Water Res.* **2019**, *150*, 140–152.
31. Schaper, J.L.; Posselt, M.; McCallum, J.L.; Banks, E.W.; Hoehne, A.; Meinikmann, K.; Shanafield, M.A.; Batelaan, O.; Lewandowski, J. Hyporheic Exchange Controls Fate of Trace Organic Compounds in an Urban Stream. *Environ. Sci. Technol.* **2018**, *52*, 12285–12294.
32. Lawrence, J.E.; Skold, M.E.; Hussain, F.A.; Silverman, D.R.; Resh, V.H.; Sedlak, D.L.; Luthy, R.G.; McCray, J.E. Hyporheic Zone in Urban Streams: A Review and Opportunities for Enhancing Water Quality and Improving Aquatic Habitat by Active Management. *Environ. Eng. Sci.* **2013**, *30*, 480–501.
33. Koryto, K.M.; Hunt, W.F.; Page, J.L. Hydrologic and water quality performance of regenerative stormwater conveyance installed to stabilize an eroded outfall. *Ecol. Eng.* **2017**, *108*, 263–276.
34. Koryto, K.M.; Hunt, W.F.; Arellano, C.; Page, J.L. Performance of Regenerative Stormwater Conveyance on the Removal of Dissolved Pollutants: Field Scale Simulation Study. *J. Environ. Eng.* **2018**, *144*, 04018039.
35. Cizek, A.R.; Hunt, W.F.; Winston, R.J.; Waickowski, S.E.; Narayanaswamy, K.; Lauffer, M.S. Water Quality and Hydrologic Performance of a Regenerative Stormwater Conveyance in the Piedmont of North Carolina. *J. Environ. Eng.* **2018**, *144*, 04018062.
36. Herzog, S.P.; Higgins, C.P.; McCray, J.E. Engineered Streambeds for Induced Hyporheic Flow: Enhanced Removal of Nutrients, Pathogens, and Metals from Urban Streams. *J. Environ. Eng.* **2016**, *142*, 04015053.
37. Vaux, W.G. Intragravel flow and interchange of water in a streambed. *Fish. Bull.* **1968**, *66*, 479–489.
38. Ward, A.S.; Gooseff, M.N.; Johnson, P.A. How can subsurface modifications to hydraulic conductivity be designed as stream restoration structures? Analysis of Vaux's conceptual models to enhance hyporheic exchange. *Water Resour. Res.* **2011**, *47*, doi:10.1029/2010WR010028.
39. Herzog, S.P.; Higgins, C.P.; Singha, K.; McCray, J.E. Performance of Engineered Streambeds for Inducing Hyporheic Transient Storage and Attenuation of Resazurin. *Environ. Sci. Technol.* **2018**, *52*, 10627–10636.
40. Kiparsky, M.; Sedlak, D.L.; Thompson, B.H.; Truffer, B.; Truffer, B. The Innovation Deficit in Urban Water: The Need for an Integrated Perspective on Institutions, Organizations, and Technology. *Environ. Eng. Sci.* **2013**, *30*, 395–408.
41. Frank, C.; Sink, C.; Mynatt, L.; Rogers, R.; Rappazzo, A. Surviving the "valley of death": A comparative analysis. *J. Technol. Transf.* **1996**, *21*, 61–69.
42. Reed, M.S.; Stringer, L.C.; Fazey, I.; Evely, A.C.; Kruijsen, J.H.J. Five principles for the practice of knowledge exchange in environmental management. *J. Environ. Manage.* **2014**, *146*, 337–345.
43. Irvine, A.; Drew, P.; Sainsbury, R. 'Am I not answering your questions properly?' Clarification, adequacy and responsiveness in semi-structured telephone and face-to-face interviews. *Qual. Res.* **2013**, *13*, 87–106.
44. Apostolaki, S.; Jefferies, C.; Wild, T. The social impacts of stormwater management techniques. *Water Pract. Technol.* **2006**, *1*, doi:10.2166/wpt.2006.009.
45. Sage, J.; Berthier, E.; Gromaire, M.-C. Stormwater Management Criteria for On-Site Pollution Control: A Comparative Assessment of International Practices. *Environ. Manag.* **2015**, *56*, 66–80.
46. *Untreated Stormwater Runoff to Lakes, Streams, and Wetlands. WQ-STRM4-28*; Minnesota Pollution Control Agency: St. Paul, MN, USA, **2019**.
47. BenDor, T.K.; Shandas, V.; Miles, B.; Belt, K.; Olander, L. Ecosystem services and U.S. stormwater planning: An approach for improving urban stormwater decisions. *Environ. Sci. Policy* **2018**, *88*, 92–103.
48. Vogel, J.R.; Moore, T.L.; Coffman, R.R.; Rodie, S.N.; Hutchinson, S.L.; McDonough, K.R.; McLemore, A.J.; McMaine, J.T. Critical Review of Technical Questions Facing Low Impact Development and Green Infrastructure: A Perspective from the Great Plains. *Water Environ. Res.* **2015**, *87*, 849–862.
49. Wolfand, J.M.; Bell, C.D.; Boehm, A.B.; Hogue, T.S.; Luthy, R.G. Multiple Pathways to Bacterial Load Reduction by Stormwater Best Management Practices: Trade-Offs in Performance, Volume, and Treated Area. *Environ. Sci. Technol.* **2018**, *52*, 6370–6379.
50. Roseen, R.M.; Ballestero, T.P.; Houle, J.J.; Avellaneda, P.; Briggs, J.; Fowler, G.; Wildey, R. Seasonal performance variations for storm-water management systems in cold climate conditions. *J. Environ. Eng.* **2009**, *135*, 128–137.
51. Blecken, G.T.; Hunt, W.F.; Al-Rubaei, A.M.; Viklander, M.; Lord, W.G. Stormwater control measure (SCM) maintenance considerations to ensure designed functionality. *Urban Water J.* **2017**, *14*, 278–290.
52. Olorunkiya, J.; Fassman, E.; Wilkinson, S. Risk: A Fundamental Barrier to the Implementation of Low Impact Design Infrastructure for Urban Stormwater Control. *J. Sustain. Dev.* **2012**, *5*,

doi:10.5539/jsd.v5n9p27.
53. Snodgrass, J.W.; Moore, J.; Lev, S.M.; Casey, R.E.; Ownby, D.R.; Flora, R.F.; Izzo, G. Influence of Modern Stormwater Management Practices on Transport of Road Salt to Surface Waters. *Environ. Sci. Technol.* **2017**, *51*, 4165–4172.
54. Houle, J.J.; Roseen, R.M.; Ballestero, T.P.; Puls, T.A.; Sherrard, J. Comparison of maintenance cost, labor demands, and system performance for LID and conventional stormwater management. *J. Environ. Eng.* **2013**, *139*, 932–938.
55. Ashoori, N.; Teixido, M.; Spahr, S.; LeFevre, G.H.; Sedlak, D.L.; Luthy, R.G. Evaluation of pilot-scale biochar-amended woodchip bioreactors to remove nitrate, metals, and trace organic contaminants from urban stormwater runoff. *Water Res.* **2019**, *154*, 1–11.
56. Nobles, A.L.; Goodall, J.L.; Fitch, G.M. Comparing Costs of Onsite Best Management Practices to Nutrient Credits for Stormwater Management: A Case Study in Virginia. *JAWRA* **2017**, *53*, 131–143.
57. Barbosa, A.E.; Fernandes, J.N.; David, L.M. Key issues for sustainable urban stormwater management. *Water Res.* **2012**, *46*, 6787–6789.
58. Hatt, B.E.; Deletic, A.; Fletcher, T.D. Integrated treatment and recycling of stormwater: A review of Australian practice. *J. Environ. Manag.* **2006**, *79*, 102–113.
59. Lane, R.; Bettini, Y.; McCallum, T.; Head, B.W. The interaction of risk allocation and governance arrangements in innovative urban stormwater and recycling projects. *Landsc. Urban Plan.* **2017**, *164*, 37–48.
60. Bahr, R.; Brown, T.; Hansen, L.J.; Kelly, J.; Papacosma, J.; Snead, V.; Stack, B.; Stack, R.; Stewart, S.; Schueler, T. *Recommendations of the Expert Panel to Define Removal Rates for Urban Stormwater Retrofit Projects*; Chesapeake Stormwater Network: Baltimore, MD, USA, 2012.
61. Hansen, R.; Rolf, W.; Rall, E.; Pauleit, S.; Erlwein, S.; Fohlmeister, S.; Santos, A.; Luz, A.C.; Branquinho, C.; Santos-Reis, M. *Advances Urban Green Infrastructure Planning and Implementation: Innovative Approaches and Strategies from European Cities*; University of Copenhagen: Copenhagen, Denmark, 2016.
62. Wolch, J.R.; Byrne, J.; Newell, J.P. Urban green space, public health, and environmental justice: The challenge of making cities "just green enough." *Landsc. Urban Plan.* **2014**, *125*, 234–244.
63. Moore, T.L.; Rodak, C.M.; Vogel, J.R. Urban Stormwater Characterization, Control, and Treatment. *Water Environ. Res.* **2017**, *89*, 1876–1927.
64. Christian-Smith, J.; Merenlender, A.M. The Disconnect Between Restoration Goals and Practices: A Case Study of Watershed Restoration in the Russian River Basin, California. *Restor. Ecol.* **2010**, *18*, 95–102.
65. Mohr, J.J.; Metcalf, E.C. The business perspective in ecological restoration: Issues and challenges. *Restor. Ecol.* **2018**, *26*, 381–390.
66. Peter Kristensen, Caroline Whalley, Fernanda Néry Nihat Zal, T.C. *European Waters Assessment of Status and Pressures 2018*; European Environment Agency: Luxembourg, Luxembourg, 2018; ISBN 978-92-9213-947-6.
67. Parrish, J. *Off-Site Stormwater Crediting: Lessons from Wetland Mitigation*; US Environmental Protection Agency, Region 9: San Francisco, CA, USA, 2018.
68. Clary, J.; Jones, J.; Leisenring, M.; Strecker, E.; Bledsoe, B.; Lammers, R. *Stream Restoration BMP Database: Version 1.0 Summary Report*; Water Environment & Reuse Foundation: Alexandria, VA, USA **2016.**
69. Bernhardt, E.S.; Palmer, M.A. River restoration: The fuzzy logic of repairing reaches to reverse catchment scale degradation. *Ecol. Appl.* **2011**, *21*, 1926–1931.
70. Kerkez, B.; Gruden, C.; Lewis, M.; Montestruque, L.; Quigley, M.; Wong, B.; Bedig, A.; Kertesz, R.; Braun, T.; Cadwalader, O.; et al. Smarter Stormwater Systems. *Environ. Sci. Technol.* **2016**, *50*, 7267–7273.
71. Hixon, L.F.; Dymond, R.L. State of the Practice: Assessing Water Quality Benefits from Street Sweeping. *J. Sustain. Water Built Environ.* **2018**, *4*, 04018007.
72. Selbig, W.R. Evaluation of leaf removal as a means to reduce nutrient concentrations and loads in urban stormwater. *Sci. Total Environ.* **2016**, *571*, 124–133.