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Article

Stormwater Management: An Integrated Approach to Support Healthy, Livable, and Ecological Cities

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Abstract: The practice of stormwater management has evolved from a singular focus on drainage to a multifaceted approach to support integrated urban development. By contributing to healthy, livable, ecological, and water sensitive cities, it is a key tool to promote Sustainable Development Goal 11 from neighborhood to metropolitan scales. A review of the knowledge base for stormwater management shows several attributes that favor an integrative approach to achieve co-benefits across several sectors. Functional areas of its contributions include drainage, flood control, flood plain management, water quality control, urban ecology, recreation, and city beautification. Legacy path dependance affects the potential to reform land use practices, while stormwater management practice is being affected by climate change, sea level rise, urbanization, inequality, and poor governance. Technical methods for stormwater management are well advanced, but integrative frameworks to address social, ecological and infrastructure needs are more challenging. The sensitivity of ecological issues is most evident in cities in coastal zones. Organizational initiatives are needed to counter neglect of essential maintenance and sustain flood risk reduction in cities. Stormwater management is related to other integrative tools, including IWRM, One Water, One Health, and integrated flood management, as well as the broader concept of urban planning. Stormwater capture and rainfall harvesting offer major opportunities to augment scarce water supplies. Nature-based solutions like low-impact development and the Sponge City concept show promise to transform cities. Major cities face challenges to sustain conveyance corridors for major flows and to store and treat combined sewer runoff. The neighborhood focus of stormwater management elevates the importance of participation and inclusion to advance environmental justice and strengthen social capital. Integrating organizational initiatives from local to city scale and funding improvements to stormwater systems are major challenges that require leadership from higher governance levels, although governments face resistance to change toward integration, especially in countries with poor land use and public works management systems. Finding solutions to neighborhood issues and the connectivity of water systems at larger scales requires complex approaches to urban planning and represent an important agenda for urban and water governance going forward.

Keywords: Stormwater management: An integrated approach to support healthy; livable; and ecological cities

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1. Introduction

Stormwater management as a field of work has been transformed from the engineering centric discipline of urban drainage to a comprehensive framework with cross-cutting linkages to other urban sectors that enables it to fill important roles in promoting healthy, livable, and ecological cities. Its concepts and methods have evolved from drainage alone, which was its main purpose as cities evolved from their earlier forms [1]. Now, its practices also embrace fields of urban planning, public health, and environmental management as its social and ecological benefits to communities at neighborhood levels are attracting more attention as understanding of the links between stormwater and sustainability increases.

The purpose of this paper is to present a review of how stormwater management has evolved as a multipurpose tool to support visions for urban development, such as those in Sustainable Development Goal 11 (SDG 11) for cities and communities [2]. This aligns with companion urban

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development goals to become healthy cities [3], livable cities [4], ecological cities [5], and water sensitive cities [6]. Each of these concepts focuses on one aspect of urban development, and their combination forms an integrated vision for future cities. Due to its multiple connections with these concepts for cities, stormwater management is taking on a central focus as an integrative tool for urban planning, design, and management [7]. Success with it offers co-benefits for safety, health, and convenience, along with social and ecological benefits at neighborhood levels, where recreation and city beautification are most essential.

Stormwater management goals face new threats from climate change, as well as challenges from urbanization, inequality, and poor urban governance, among other threats [8]. As governments respond, they face resistance to change toward needed integration, which can lead to poor stormwater services, deteriorating systems, and inequities. These problems are greatest in developing countries, where poor land use and public works management systems are common.

As stormwater management has evolved, reviews of its technical parts have been published and will be summarized here. New proposals for integrative frameworks of stormwater management have been advanced, but their effectiveness as system integrators has not been explained, especially about how to address social, ecological and infrastructure needs together. This paper offers a scan and summary of the emerging broader knowledge base for stormwater management that considers these integrative methods and their co-benefits across several sectors. It begins by summarizing work on technical issues of stormwater and extends the discussion into arenas of urban planning and development that address collective action toward cities that are vibrant, livable, and healthy [9].

The review begins with a background discussion of drivers of change and situations faced, to include hydrologic change and evolution of the technical subfields of stormwater management such as urban hydrology and modeling. A discussion of how stormwater management relates to flood risk reduction programs in cities focuses on emerging integrative methods in that sector. Water quality management issues are inherent in stormwater control, and use of stormwater capture as a resource provides a lens through which to view One Water aspects [10,11]. Most information is about cities in developed countries where stormwater management is most advanced. The greater challenges faced by developing countries are due to socioeconomic conditions that affect local governance systems, especially for land use control and public works management. A brief discussion of challenges in developing countries is offered to highlight these land use and public works management issues. The discussion then turns to urban planning topics that include land use, low impact development (LID), and amenities such as city beautification and recreation. The environmental aspects of stormwater management are emphasized in a short discussion of how they relate to healthy and ecological cities. The key issues of organization and finance are discussed to signal and explain the importance of policy, governance, and administration. Ultimately, the major advances needed in stormwater management align with the goal to build social capital, and the discussion concludes with how integrative frameworks can contribute to it. Taken together, these perspectives form an integrated view of how stormwater management can play a greater role in achieving shared goals for future cities, as outlined in SDG11.

2. Background and Chronology

Stormwater management is usually defined by its role to manage excess water generated by rainfall, mainly from runoff from impervious surfaces such as roofs, streets, and parking lots [12]. A broader hydrologic concept explains how it infiltrates into the soil in pervious areas, where it replenishes aquifers and becomes tributary to streams and rivers. Nature-based green infrastructure systems are intended to facilitate such infiltration. Reviews of the evolution of stormwater management address both focus areas.

The general technical background has been reviewed by multiple authors [1,13]. The evolution of stormwater practices varied with location and context, and most data are from Europe and North America for the period of greatest change that began late in the industrial revolution. Prior to 1900, street and site drainage systems were being expanded, and building sewers were being connected to

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storm drains, thus creating combined sewer systems. After 1900, there was an expanded need for street drainage to accommodate growth in road mileage due to automobiles.

The development trajectories of cities diverged after World War II due to the physical destruction that occurred in Europe and Asia as compared to the United States, where central cities had remained intact until the 1950s. Then, the new Interstate Highway Program created a leapfrog effect that led to rapid suburbanization and expansion of storm drainage. The 1960s exposed new stormwater quantity and quality problems in growing cities, and the methods of urban hydrology developed rapidly in response [14]. When this writer began to practice stormwater engineering and management during the 1960s, a new stormwater management agency in the Denver, Colorado region took shape with the name “Urban Drainage and Flood Control District,” thus signaling the terminology and focus of the time. This new special political district also provided a mechanism for integration across the metropolitan area [15]. This was also a period of growing interest in preventing flood damage and included development of the NFIP in the US [16].

Up to about 1970, stormwater management stayed mostly in the realm of public works management, which is a common function within local governments. However, rapid urbanization and climate change began to take a toll that included rising flood damages, impaired transportation systems, water quality degradation, bank erosion with loss of land and sedimentation, and ecosystem damage. As cities began to address the issues, management approaches had to become more comprehensive. Leading thinkers were seeing the need for emerging methods such as “blue-green” stormwater systems [17] and non-structural flood control systems [16]. This led to 1970s detention storage, blue-green systems, and stormwater quality control. What is known today as green infrastructure was in the minds and goals of innovative planners and engineers over 50 years ago. Now, such practices extend broadly to several planning-related professions.

In Mega-cities, there was not enough space to store stormwater to mitigate problems, and tunnels began to appear [18]. These were also used to help control CSOs by use of automatic control systems. The writer worked with public works officials during the 1970s in studies of automatic control systems for CSOs in major US cities [19], and current approaches seem to be following the trajectories established in that era.

During the rising interest in blue-green systems, connections between engineers and urban planners began to strengthen and to be implemented with concepts like LIDs. Now, new threats and changes due to climate change, need for greater social equity in cities, and governance challenges must be faced. These require extension of stormwater management concepts beyond the technical realms of past years.

3. Stormwater and Land Use in Developing Countries

While some issues of stormwater management systems are similar in different settings, land use and public works management have substantial effects on them. Land use involves management of streets, structures, and open spaces, which determines the capacity of drainage systems to function effectively. If it is not managed to provide an orderly arrangement, drainage flows can be blocked and cause undue flooding, damages, and disease. It is affected by the phenomenon of path dependence, which means that current possibilities are constrained by past events.

Land use control systems vary between developed and developing countries. In developed countries, urban plans will normally be based on policies that set the structure and principles of city development. In the US, these plans will vary among states, and cities with rapid growth will face more issues than those with stable populations. In developing countries, more conflicts are to be expected, including those between formal and informal settlements. Operation of the rule of law and the effectiveness of local governance will be key to achieving the orderly arrangements needed to facilitate stormwater management [20].

Public works management by local governments involves multiple measures to apply resources toward solving ongoing problems of urban systems, and stormwater is one its central concerns. The effectiveness of local public works management is a key issue in determining stormwater system performance. The aims of public works programs differ somewhat among countries by income. In the US, they have been defined by the American Public Works Association (APWA) as "the combination of physical assets, management practices, policies, and personnel necessary for government to provide and sustain structures and services essential to the welfare and acceptable quality of life for its citizens" [21apwa]. Having served on the national board of directors of APWA, this writer witnessed the skill with which the public works managers in high income countries managed their stormwater systems. However, in developing countries public works management may focus more on poverty alleviation by providing employment, and the key issues will be governance, availability of resources, and the efficacy of the management level [22].

Review of stormwater management issues in selected developing countries showed that they face the same technical and management complexities as richer countries but encounter additional difficulties due to the greater incidence of poverty and difficulties in land use control and public works management [23]. Difficulties are evident in Brazil, for example, where like other nations at similar levels of development, the nation has many residents living in vulnerable informal settlements. A review that included a survey in Brazil showed barriers such as lack of design and maintenance standards, long-term planning, dissemination and knowledge, and incentives. Also, they face the same problems with reluctance to change as is evident in developed countries [24]. Many developing cities are experiencing large scale urbanization and, along with climate change effects, this causes massive urban flooding in low-lying regions, such as experienced during the record 2024 flooding in Southern Brazil [25]. The physical aspects of such stormwater and flood problems are compounded by social problems such as disorganization, poverty, and lack of management, as was explained in [26]

Problems in developing countries vary with context. For example, in Indonesia a survey conducted of flood-related problems in Jakarta included interviews with local officials, academicians, researchers, consultants, non-governmental organizations, and citizen communities. Most respondents saw natural and technical factors as the primary causes of severe urban flooding, and most did not know about flood mitigation programs or flood regulations. Most did not receive any flood warnings, despite record flooding. About half of respondents lacked any action to make their homes flood-resistant, although they expressed great concern on reducing flood risk in their area. Lack of trust in the government was evident, and the majority felt that government has not been responsive enough [27].

The examples in Brazil and Indonesia are from humid zones with large floods, but stormwater damage can occur even in arid zones. Land use and public works management are the two urban programs with greatest influence on preventing damage and developing countries face many issues in both program areas, along with the likelihood that governance is in a state of confusion [28].

4. Technical Issues of Stormwater Management

The main driver of demands on stormwater systems is excess rainfall, both volume and intensity, which are addressed by the field of urban hydrology, which advanced rapidly beginning after 1900 as it emerged as an important subfield of hydrology [29]. By the 1960's, the American Society of Civil Engineers (ASCE) had organized an Urban Hydrology Research Council, which became the Urban Water Resources Research Council and has pursued diverse topics since [17]. Participants, along with colleagues from other countries, were exploring issues in urban hydrology such as runoff coefficients, the Rational Method, and unit hydrographs. The state of the art of the time was compiled into an Urban Storm Drainage Criteria Manual that was prepared after a disastrous 1965 urban flood in Denver, Colorado [15]. Similar manuals have now been developed elsewhere, some in greater detail as in the UK [30].

Hydraulic methods were also evolving, and the Stormwater Management Model (SWMM) was developed during the early 1970s [31]. Other models have followed, such as work by the partnership of the Institute of Hydrology in the UK, the Danish Hydraulic Institute (DHI), and SOGREAH (Société Grenobloise d'Études et d'Applications Hydrauliques) in France, which developed the Système Hydrologique Européen (SHE). This led to additional urban models, including MIKE SHE (DHI) [32], which can be adapted to stormwater situations [33].

The models required data for calibration, and much more rainfall data are available than in the early days of urban hydrology. Many urban locations have site-specific studies and radar data are becoming useful for nowcasting of urban flash flooding [34, 35]. Collection of runoff data in sewers was facilitated by development of meters, and now many cities are monitoring stormwater quality and quantity [36].

Stormwater detention systems began to evolve about 1970 [37, 38] and later, deep tunnels were instituted to manage combined sewer overflows and flooding. Management of tunnels can be facilitated with effective monitoring and control strategies, which require real-time system models and forecasts [39]. The oldest reported tunnel was in Chicago, where the chief planner, Victor Koelzer, trained the writer to teach a water resources management course at Colorado State University. In his course, Koelzer played a video of a television exposé of claimed government over-expenditure on the tunnel [18]. The claim has disappeared, and now many other cities are implementing tunnels, including London, which requires it to reign in pollution in the Thames River [40, 41].

Some complex stormwater systems require automatic control models to use optimization together with simulation models [42-44]. The application of such systems will increase with rising capabilities of AI and machine learning [45], and digital conversion will push their management toward becoming intelligent systems [46].

Best management practices (BMPs) for stormwater have been implemented for several decades and the International Stormwater Best Management Practices Database (BMPDB) was established in 1996 as a repository of studies, tools, performance data, and guidance. It expanded from its original focus on urban stormwater control measures to add agricultural runoff, treatment, and stream restoration. The database was originally managed under a cooperative agreement between ASCE and the US Environmental Protection Agency (USEPA), and management has been assumed by a coalition of partners led by The Water Research Foundation (WRF) [47].

The advances in stormwater engineering and management require organizational initiatives to counter the tendency to neglect essential maintenance [48]. One has been the stormwater utility in the US, which began as a reaction to anti-tax movements that resisted public expenditures for stormwater management. The utilities provide an essential mechanism to promote effective system maintenance and operations with adequate funding and management via performance reporting.

Flood risk reduction in cities is a stormwater issue but also a matter of disaster and emergency preparedness. There is not a sudden divide between matters of stormwater management and flood risk reduction, although the professional communities addressing them are somewhat distinct. Developed countries experience urban flooding, but the major issues are in developing countries that lack land use controls and organized management systems. In the US, for example, hurricane-induced flooding afflicts cities near the Gulf and East Coasts, with the Katrina flood in 2005 leaving indelible marks on the City of New Orleans and Hurricane Harvey causing massive flood damages in Houston, Texas [49, 50].

Urban flooding is difficult to define consistently, and damage statistics are uneven due to definitions of urban settlements differing among countries [51]. Many settlements in developing countries are under flood threat, and the general issues are being addressed at the global level by the Associated Programme on Flood Management (AFM) [52]. The AFM defines Integrated Flood Management as "a framework that promotes sustainable, long-term flood resilience by combining social, economic, financial, environmental, and institutional solutions, as well as those involving engineering, disaster preparedness, insurance, and emergency response" [53]. Although the definition aims toward extreme events, the application of IFM in cities supports integrated approaches to stormwater management.

Capturing stormwater as a resource has become more attractive, and a report indicated that available stormwater could equal 93% of US municipal and industrial water withdrawals in 2015. Coastal areas offer the most opportunities, have fewer adverse impacts, and improve water quality in coastal waterways. Challenges focus on ecological issues and legal constraints, which dominate where water is scarce [55]. The general issues are discussed in [56], which reviewed experiences and needs to move forward.

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Rooftop rainwater harvesting is practiced widely in developing countries [57]. As examples, pilot projects in Semarang, Indonesia [58] and in Tanzania [59], where socio-technological challenges are prominent. The case focused on a primary school where a gauge was used to monitor storage and simplify quantity control and the utilization strategy. A participatory approach with training to manage the system included a maintenance manual to promote a sense of ownership. The study proposed strategies for developing countries that include regulations and research centers, financial stability, demonstration projects, and investment by governments to promote the systems.

As urban planners study land uses toward creation of high-quality cities, the primary consideration related to stormwater should be to reserve space for its conveyance from sites to discharge points. If the rate and quantity of runoff can be controlled, impacts will be much less, which forms a basis for emerging LID approaches. Stormwater runoff also drives water quality impacts, especially the "first flush," so controlling it at the points of origin has multiple benefits. Sustaining natural conditions where runoff occurs also helps sustain urban ecology. When stormwater facilities are co-located with recreational spaces, healthy cities are facilitated, and the combined effects can help with city beautification, which is a central goal of planners.

The traditional technical approach to urban drainage has been to use gutters, inlets, and pipes to collect and convey runoff water to discharge points in local streams. For planning purposes and because flows vary in magnitude, it is convenient to separate them into minor and major categories, with emphasis on the distinction between convenience drainage and flood control. While this distinction is measured by the flood frequencies driven by precipitation, it also figures into land use planning in that minor flows can be handled by street and drainage systems, whereas major flows require larger conveyance spaces that must be provided without threatening flood damage to properties. Such requirements were illustrated, for example, by a major storm that struck Ellicott City, Maryland on July 30, 2016 and caused two deaths [60]. Local minor facilities were overwhelmed, and the flood caused major damage in the city. As it went through the historic district, a conflict about conversion of land use to accommodate flood conveyance was evident. In newer communities, flood conveyance routes should be built into the plans.

Retaining or reducing stormwater flow volumes and rates at points of origin is the goal of the low-impact development (LID) methods that have been emerging. LIDs must be planned to achieve optimal performance levels [61]. A bibliometric review showed that research on LID-based methods is popular, but there is a divergence between international perspectives and those in China, where the focus has been on practical problems related to construction and engineering. This is made necessary due to water-related issues caused by land use changes in China. Other countries have focused more on environmental issues, such as water quality and runoff reduction. Research was focused on small scale issues and current emphasis is pointing toward expansion to macroscopic views and coordination with infrastructure and water networks toward more systemic views [62].

LID is closely related to the sponge city concept, for which the name originated in China with a 2013 policy framework. A sponge city involves multiple measures to control and manage runoff, including surfaces to absorb water such as green roofs and swales with permeable soil layers, which double as conveyance channels for runoff. Green areas and swales also treat polluted stormwater [63]. A bibliometric analysis showed a large rise in articles about it in the last decade [64]. Assessment of the program so far has resulted in lessons learned that some sponge cities still are experiencing flooding due to problems like connectivity between catchments [65].

Nature-based solutions can be sustainable solutions for stormwater management, and they are a basis for sponge cities in China. Community-based measures in China can include mapping, site-based measures, flood insurance, and social capital-building toward flood resilient communities [66].

Studies on the impact of stormwater runoff on water quality began more than 50 years ago with the 1972 Clean Water Act, although it took legal action for several years before a regulatory program was established. The knowledge base has grown to be very large, although conditions vary, so general conclusions remain site-specific. This has spurred much research about best management practices and assembly of the BMP data base. In the EU, stormwater regulation came somewhat later, but has been included in the Water Framework Directive (WFD) and the Floods Directive, although implementation varies among member countries. While water quality is very important, its management depends on effective regulation and maintenance, which are challenging [67]. A major issue in cities of Europe is combined sewer overflows, which has proved a thorny problem in London, for example, and is a main reason for construction of a major stormwater tunnel [54]. Research to illustrate its linkage to urban planning shows that water quality is better for high-density development than distributed development [68]. Emerging research topics include use of wetlands for treatment and application of intelligent controls [69, 70].

5. Cross Sector Impacts and Integrative Frameworks

Following its tech-centric nature, the starting point for an integrative framework for stormwater management is the One Water concept, where rainfall runoff, drinking water, wastewater, and recycled water services are managed jointly. Such an approach may be blocked when stormwater is considered a site-specific issue for engineers to develop specific infrastructure plans. This narrow framing blocks its use in land-use decisions using a broader landscape perspective and opportunities for co-creation of benefits. If such issues lack clear ownership or institutional affiliation, budgets will be restricted to sectoral investments and block cross-fertilization of concepts. Stakeholders will be segregated according to roles and not able to become cocreators to express their ideals for stormwater management outcomes. Management at the watershed level can facilitate integration, and direction by central cross-sector offices, use of networks to facilitate mutual learning and dialog, and assessment of outcomes of plans are needed [71].

As it becomes more comprehensive, stormwater management fits within other integrative frameworks for urban systems. The term integrated stormwater management can be used to emphasize alignment with ecosystem-based measures and human systems through participatory approaches that create economic, social, and environmental co-benefits. Integrative frameworks like Water Sensitive Urban Design (WSUD) offer new ways to link water management with urban planning, which is itself an integrated framework. IWRM encompasses the water and land use management elements needed, but it is more general and extends beyond urban settings. One Water as an integrative framework lacks a focus on cross-sector links outside of the water arena. Integrated Flood Management focuses on the single objective of flood risk reduction. The Sponge City concept as an integrative framework fits with urban planning and use of tools such as LID to seek co-benefits to other sectors [72].

Within the context of urban planning, sectors that can offer co-benefits from links with stormwater management are urban ecology, public health, recreation, and city beautification as an amenity sector. Links of stormwater to urban ecology are with nature-based solutions, especially in coastal areas [73, 74]. Urban ecology is complex, and management schemes may not work for all species, which provides an important reason for a multiplexed view of planning. This problem is evident in the linkage of roads and culverts as stormwater features as factors in species and biodiversity losses [75, 76].

One Health is an integrative framework that captures the relevant health goals inherent in stormwater management. It is generally defined as an approach to balance and optimize the health of interdependent people, animals, and ecosystems. It recognizes the need to merge health, food, water, energy, and environment as wide topics with sector-specific actions that affect health issues like infectious diseases, antimicrobial resistance, food safety, and integrity of ecosystems. One Health applies at levels from the community upwards where people must understand co-benefits, risks, trade-offs, and opportunities for equitable and holistic solutions [77].

The One Health concept can be applied to the links between stormwater management and healthy cities [78]. Green infrastructure in parks can attract people to the outdoors [79]. As an example, a 50-mile trail system has been created along a legacy irrigation canal in Denver, Colorado, and the logical agency to maintain it is the local stormwater district [80]. Water attractions in inner cities offset some of the problems of hot weather and will become more important with rising temperatures [81]. Safety issues must be observed, including barriers to underground conduits, prevention of drownings, and alerts about hazards of low head dams [82].

Ponds and lakes, along with natural features like wetlands and native vegetation can improve visual effects in cities. The use of such features to make cities more attractive is consistent with the sponge city concept and can offer a new era like the "City Beautiful" movement, which was a late-19th Century emphasis on urban planning. It was preceded by social movements as precursors to development of city planning in the US that included public health, sanitary reform, housing reform, and parks planning. There was also a Garden Cities Movement in England, and both influenced planning in the US. Now, stormwater management offers to provide new energy to such planning initiatives [83].

In contrast to less institutionalized integrative frameworks, urban planning stands out as a long-established and organized interdisciplinary field that embraces stormwater management as an important tool [84]. Urban planning has academic departments, degrees, specialties, textbooks, journals, and wide recognition and is a good venue to extend awareness of stormwater management benefits and methods. A version of it named "integrated urban planning" is defined as a participatory and agile process to advance work across agencies, jurisdictions, and sectors, exactly what is needed to use stormwater management as an integrative tool [85]. Stormwater management is also considered as an important knowledge element within fields related to urban planning, such as landscape planning [86]. Among urban planners, water has long been recognized as an important element for use in shaping the urban environment [87], and stormwater management can link it to other urban systems.

Recognition of stormwater management co-benefits has been institutionalized through a planning tool named the Community-enabled Lifecycle Analysis of Stormwater Infrastructure Costs (CLASIC) tool [88]. The tool is used for feasibility analysis of green, green-gray, and gray infrastructure and provides a life cycle triple bottom line benefit analysis to include environmental, social, and financial co-benefits, as well as performance assessment of stormwater quantity and quality goals. The tool has been demonstrated in several scenarios that include various combination of stormwater options and categories of co-benefits.

6. Participation and Inclusion in Stormwater Management

There is a substantial knowledge base about environmental injustices, with the most visible impacts of poor stormwater management are seen with neighborhoods paved over and lacking in green spaces with benefits like the sponge city. In addition to lack of adequate stormwater facilities in the first place, poor management and lack of maintenance of even basic systems increases threats from flooding, erosion, water quality deterioration, and ecosystem losses [89].

By addressing such issues in communities, stormwater management offers a way to improve participation and inclusion of all residents in decision-making and community management. Other water services, especially water supply and wastewater, are managed by businesslike utilities and private individuals as users lack direct management opportunities. In contrast, local land use and stormwater tasks such as maintenance of parks, ponds, and canals, are within reach of residents and can be handled without formal government involvement by organization of civic and neighborhood associations.

Stormwater is linked to larger scales through hydrologic networks, but its primary social implications are at the neighborhood or small community scale. How stormwater management is managed at that scale affects social fabrics in several ways, especially in participation and a sense of belonging [90]. While affluent areas usually have land use codes and other restrictions, disadvantaged cohorts of people experience housing insecurity and are often excluded from land use decisions. Stormwater management offers opportunities to build trust and community social capital by empowering them through valid and effective participation [91].

The main ways to empower people and communicate the value of stormwater management are by effective public engagement. The starting point is communication to find out what they want and need, and social scientists embed themselves in communities to learn about these. Building trust this way may not be possible in brief and periodic meetings, but community advisory boards in neighborhoods can help by involving local stakeholders. These boards must involve the right people,

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who must be empowered and sometimes compensated. Events like open houses and presentations, along with stakeholder interviews and online engagement may also help, and some communities, like religious groups, may be especially helpful. In addition to the main benefits of stormwater management, community gardens may be useful to offer co-benefits and build trust. They might be developed, for example, on problematic brown-scape properties [92].

Research shows that members of the public hold strong views about stormwater management, even when they lack specific information. For minor drainage, opinions focused on amenities, recreation, and aesthetics values are important, while function, efficiency, and maintenance are important in areas subjected to more extensive flooding. People have shown that they appreciate sustainable projects like river restoration more than they do hard infrastructure systems.

Abundant information is available about stormwater management and environmental justice, and some cities are using their connections in local decision-making processes for community improvement [93]. Such issues are beginning to find a place in schools relating to planning, such as the School of Architecture, Planning and Preservation at the University of Maryland, which has a Stormwater Infrastructure Resilience and Justice (SIRJ) Lab [94]. Another example is the School of Social Ecology at the University of California at Irvine [95].

7. Stormwater Management Organization and Finance

If integrated stormwater management is to succeed, much of the work will be needed in the organization and finance arenas, which are mostly provided by local governments due to the scales involved and jurisdictional responsibilities. Current governance supports conventional approaches and does not lend itself to integrated methods with multiple stakeholders. Methods to overcome the problems with innovative approaches are available, but they face resistance to change [96].

A study of governance for urban planning in Sweden focused on resistance to change in organizations. The example used was stormwater as a technical challenge for engineers, while nature-based solutions require an approach based on landscapes and ecosystems. The researchers found that traditional planning approaches see stormwater management as a site-specific technical issue, which segregates it from land-use decisions. Also, organizational procedures may constrain cross-sectoral cooperation. The authors recommended stormwater assessments at the watershed level as a basis for comprehensive planning and transfer of leadership from sectors to a central office with a mandate for coordination and control.

The same issues were observed in Sidney, Australia. Implementation of integrated stormwater management approaches has been limited, despite years of trials. Inertia with administration of urban stormwater perpetuates traditional stormwater management practices. Historically entrained forms of technocratic institutional power and expertise, values and leadership. There is a need to foster horizontal integration of the functions of administrative. capacity-building targeted at enabling a learning culture that values integration and participatory decision making [97].

Some US cities have adjusted their governance approaches, and multijurisdictional drainage agencies such as the Mile High Flood District in Denver mentioned earlier can organize coordinated approaches. At the micro-scale and site levels, citizen involvement can work like neighborhood associations and be coordinated with formal governance involving government authorities [98].

Funding stormwater management systems has proved challenging due to the mixture of types of public goods they provide. Local governments require dedicated funding sources, and countries have been experimenting with diverse approaches to stormwater fees. Among nine countries studied and reported in [99], France had the highest fees, but it was suspended in 2014. Brazil and the US had lower fees. The US was the most experienced in stormwater funding practices among those studied.

Studies of how to reform institutions to promote cooperation show analysis of case studies. The writer participated in a study with three sources that contain some 63 cases claimed to be One Water examples. These were reduced to 36 by data cleaning. The study identified primary financial practices to promote One Water, including leadership by a regional governing council to allocate funds to facilitate its implementation. Grant funds from higher levels of government work, especially when equity issues are involved. Grant programs were more attractive when they addressed multiple

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issues. The indication is that policy makers should create authorities with the power to assemble mixed funding, tax, grants, contributions, service fees to recognize the need for cross-sector work [100,101,102].

8. Conclusions

The study reported here showed that technical advances in stormwater management have created effective methods to analyze and plan for small to large rainfall events, but there has been less progress in the organizational and management strategies needed for cross-sector integration and provision of service to all stakeholders. The situations requiring technical methods involve assessment of hydrologic and land use changes due to natural and human causes. Models provide the needed tool sets, but better hydrologic, hydraulic, land use, and water quality data are needed to validate them. Use of BMPs to improve water quality shows promise but maintaining them to sustain high performance levels is a continuing challenge.

In the largest cities spatial problems lead to major infrastructure requirements to address storage and conveyance of stormwater runoff and is leading to implementation of the sponge city concept, in which storage and absorption are provided locally to control discharges, treat contamination, and recharge groundwater aquifers. In large cities such as Chicago and Tokyo, stormwater tunnels are used to provide additional storage. These tunnels contribute to controlling overflows from combined sewers as well, and they require decision support systems and automatic controls to facilitate effective use of the infrastructure. In London, a major tunnel has just been completed with a goal to reduce contamination caused by combined sewer overflows.

The need for safe conveyance of rare storms is becoming more urgent as climate change and sea level rise increase risks, especially in coastal areas. Major stormwater systems with conveyance corridors must be planned in conjunction with minor systems, and systemic planning is needed to assess the connectivity of water features. This is a major issue in cities where uncontrolled land development has closed off needed flood corridors. Climate change and resulting major storms also signal the need for effective forecasting and smart systems to operate controls that minimize adverse effects. Research is focusing on use of the IoT to control small scale actuators, along with AI and machine learning to develop better decision support systems based on real-time monitoring.

The integration of physical systems is advancing with popularity of the One Water concept for water supply, wastewater, stormwater, and recycled water. The example of Singapore Water continues to draw attention for its success to address difficult supply issues with local initiatives. Stormwater capture for potable and non-potable supply has been shown to have considerable potential, although legal issues in dry regions may sometimes pose barriers. Rainwater harvesting in developing countries is a companion issue, with attention given at the micro-scale to supplies from single roof structures and pavements.

The organizational structures needed for runoff control are usually provided by urban public works departments, which can have different names and functions. These may be separated from water supply and even wastewater organizations, but they have common engineering orientations and can cooperate to plan and manage the interdependent systems when barriers due to resistance to change can be overcome. Elevating the integration of systems to embrace land use issues requires a broader concept of cooperation. Land use issues where stormwater is central include floodway and floodplain management, water quality, recreation, and city beautification. Success in integrated approaches to incorporate these requires effective urban planning and management, but many barriers impede the needed efforts. The main challenge is that traditional planning considers stormwater management as mainly a technical and site-specific issue, and this tends to depoliticize land-use decisions that require cross-sectoral budgets.

Research shows that formal and informal institutional arrangements can be structured to facilitate cooperative, integrative approaches, but formal structures sometimes inhibit development of sustainable solutions with landscape and ecosystem approaches rather than only constructed infrastructure. Informal institutional arrangements, such as networks and relationships, can create incentives to foster cocreation cultures and mindsets. Suggestions for these should be directed to a broad set of policy makers and planners. Leadership of projects, as well as funding for joint solutions, can best be handled by higher level authorities, rather than sectoral boards.

In terms of integrative frameworks, stormwater management and the One Water concept support One Health goals. Poor quality of stormwater exposes humans to pathogens, and when stormwater and trash are mixed in disorganized settings, additional disease vectors find fertile ground to threaten people. Stormwater supplies for urban farming can bolster local food supplies and linking stormwater conveyance with recreational outlets like trails along canals can promote the fight against obesity. The concept of the healthy city connects naturally to the ecological city. Nature based stormwater solutions will be a key component of multiple measures to improve urban ecology. The sensitivity of ecological issues in cities in coastal zones requires special attention.

Effective stormwater management is important to social justice via the daily experiences of people at the site level, especially when runoff events are frequent and heavy. When crowded conditions and lack of land use control result in contaminated waterways with residents having little say or opportunity for improvement, disease outbreaks become more likely. The example cited of drainage along canals in Jakarta provide a stark picture of this problem. Also in Indonesia, lack of control of groundwater pumping leading to land subsidence and increased flooding promotes growth of disease vectors, and residents are powerless to take remedial measures.

Success in integrated stormwater management can strengthen social capital in communities, and it requires cooperative approaches with public engagement by authorities and cooperative approaches by social and civic associations, beginning at the neighborhood level. Involvement of officials at the metropolitan level is needed because the capacity of neighborhood leaders to address regional problems is limited.

Research shows the need for governance reform to empower residents at the neighborhood level to work together to solve their local problems and to address the connectivity of drainage systems at larger scales. However, there is little information on successful policies, institutions, and regulations to achieve this. The subject is complex due to multi-disciplinarity, involvement of diverse actors, many formal and informal rules, and strong path dependence whereby possibilities are constrained by the past and by inertia in local contextual situations. The goal to provide effective governance for stormwater at the site through metropolitan levels and with social justice in mind poses a major challenge for civic leaders.

Ultimately, stormwater management provides a poster child for the need for integrated approaches like IWRM and One Water. They involve complex physical, social, and ecological systems that require actions for infrastructure, land use, and civic improvement. Legacy path dependance and organizational stovepipes inhibit cooperation and require definite approaches for cross-sectoral management arrangements. Financing integration is difficult because the co-benefits have different beneficiaries. Finding ways to address neighborhood issues and the connectivity of water issues at larger scales represents a major challenge for urban and water governance going forward.

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