Water **2013**, *5*, 29-52; doi:10.3390/w5010029

OPEN ACCESS

water

ISSN 2073-4441

www.mdpi.com/journal/water

Article

Stormwater Governance and Future Cities

Erik C. Porse

Department of Civil and Environmental Engineering, University of California, Davis, One Shields Ave., Davis, CA 95616, USA; E-Mail: eporse@ucdavis.edu; Tel.: +1-530-752-9708; Fax: +1-530-754-9364

Received: 14 November 2012; in revised form: 4 January 2013 / Accepted: 6 January 2013 / Published: 14 January 2013

Abstract: Urban stormwater infrastructure traditionally promoted conveyance. Cities are increasingly designing stormwater infrastructure that integrates both conveyance and infiltration in hybrid systems to achieve public health, safety, environmental, and social goals. In addition, cities face decisions about distribution of responsibilities for stormwater management and maintenance between institutions and landowners. Hybrid governance structures combine centralized and distributed management to facilitate planning, operations, funding, and maintenance. Effective governance in any management approach will require changes in the expertise of stormwater agencies. Recognizing the distinction between hybrid infrastructure and hybrid governance is important in long-term planning decisions for construction and management of stormwater systems. A framework is presented that relates the level and type of existing stormwater infrastructure with available capital, institutional development, and predominant citizen contributions. Cities with extensive existing infrastructure are increasingly integrating distributed, "green" approaches that promote infiltration, and must improve institutional expertise for governance decisions. For cities with little existing infrastructure, landowner management often dominates, especially when municipalities cannot keep pace with rapid growth. In between, rapidly industrializing cities are positioned to use growing capital resources to fund both conveyance and infiltration measures based on current design principles. For all cities, local management innovations, including decisions regarding public engagement, will be critical in shaping future urban stormwater systems.

Keywords: urban; stormwater; governance; distributed; sustainability; institutions

1. Introduction

Cities are dynamic entities of overlapping social, economic, environmental, and infrastructure systems. Urban infrastructure serves an increasing proportion of the human population [1]. As cities grow, existing infrastructure is integrated with new approaches and technologies, creating systems that are linked across both physical and temporal scales. Since the early twentieth century, stormwater management has primarily emphasized centralized, structural approaches that promote conveyance and retention, including storm drains, sewers, tanks and basins, and treatment facilities. Increasingly, cities are experimenting with approaches that reduce runoff and pollution by increasing managed infiltration through natural hydrologic features, often referred to as green infrastructure or low-impact development (LID) [2–5]. Such systems are hybridized and designed to promote both conveyance and infiltration. At the same time, many cities lack any existing stormwater systems for large areas. Such cities expand stormwater services for residents by implementing both centralized and distributed approaches appropriate to climate, hydrology, and development characteristics in the region.

A long history of urban research has explored the interaction of cities with their environments [6–14]. Stormwater management grew out of twentieth-century efforts to provide centrally-managed services to residents of rapidly-growing cities that increased public health and flood control [15,16]. Increased awareness of the environmental impacts of industrialization, along with greater scientific understanding of urban ecological processes [17–20], has spurred a new era of urban development that pursues multi-disciplinary, "sustainable" goals. This planning approach considers energy use, ecology, and landscape design to mitigate pollution, reduce consumption, and improve social equity in cities [21,22]. Yet, many cities retain legacy systems, such as combined sewers, which degrade surrounding ecosystems. Alternatively, many industrializing cities struggle to provide basic infrastructure and services that promote healthy environments for residents.

Stormwater management goals are evolving beyond conveyance and flood control, to include pollution abatement, runoff retention, urban landscape improvements, and reduced infrastructure costs [23]. Stormwater systems today are expected to serve more functions, while still remaining cost-effective [24]. Some regions, including Australia and Scandinavia, have a longer history of emphasizing water recycling and integrated stormwater management [25–27]. Other industrializing cities suffer greater scarcity of human and monetary capital for building reliable infrastructure that augments limited (or non-existent) distributed stormwater management. As stormwater infrastructure approaches change in cities throughout the world, the organization of stormwater management is important for ensuring reliable and cost-effective operations.

This paper reviews literature on governance and stormwater management to consider how governance structures may change as hybridized urban stormwater systems evolve. It draws a distinction between hybrid approaches for stormwater infrastructure and hybrid approaches in stormwater management and explores their ramifications of municipal decisions. The paper also presents a framework to understand how existing stormwater infrastructure, availability of capital, and citizen responsibilities influence development of more hybridized systems in cities of different climatic, income, and demographic characteristics. The heterogeneity of cities makes a comprehensive framework challenging. This article attempts to balance the usefulness of a comprehensive framework with the need to recognize local nuances of urban development as a contribution to planning and management for sustainable urban stormwater systems.

2. Understanding Governance for Stormwater Systems

Governance typically describes rules for decision-making involving many stakeholders, including individuals, civic organizations, and government institutions, in the context of laws and policies [28,29]. Governance is distinguished from governmental actions to recognize flexibility, decentralization, and inclusiveness of private and community participants, who may have established, extra-governmental processes for managing environmental resources [30,31]. Public agencies have a broader set of available policy tools than typically recognized, including market-based approaches [29,32]. Water governance describes the range of actors, institutions, and organizations that contribute to water management at many levels [33,34]. Governance is also defined as collective actions coordinated among various stakeholder groups towards a watershed goal, often distinct from watershed governing undertaken by governments or utilities [35]. Cities worldwide face a variety of complex challenges related to stormwater governance, including: diminished or non-existent funding, uncertain or uncontrolled land development; inadequate data availability; legacy systems that pollute; integration of new and existing infrastructure; environmental quality requirements; and uncertain hydrology. Governing institutions are products of past political decisions, but also adapt to reflect future goals of societies.

Brown *et al.* [36] reviewed governance literature related to water management. Three idealized governance approaches include: hierarchical governance by formal institutions [28]; market governance that allocates resources through market mechanisms [32]; and network-negotiated governance, founded on interactions and agreements among network participants and stakeholders [28]. In some cities, institutions for water governance are well-established. Saleth and Dinar [37] argued that water-related institutions are often hierarchical and embedded in the technological, social, political, and economic contexts of a state or nation, but change can be motivated by both endogenous (water scarcity and water conflicts) and exogenous (economic development, demographic growth, and technological progress) factors. Neimczynowicz [26] noted that a challenge for water management is to "organize crosssectoral [sic] cooperation between multiple actors to introduce innovative technologies, management systems, and institutional arrangements which can meet multiple objectives." Technologies and approaches to manage water effectively in the coming century already exist, but promoting cooperation in water management among participants is a continual challenge.

Institutions that manage urban water systems, and stormwater specifically, have evolved to meet performance goals. During the last century, urban water systems were typically designed to be large and centralized, seeking efficiency and stability through economies of scale. Accordingly, management structures and associated institutional knowledge emphasized rational planning that maintained adequate supply and sanitary conditions within financial constraints. Stormwater agencies used risk assessments for flooding to design conveyance capacities [36]. These systems contributed to impressive improvements in public health and flooding reductions for urban residents in many cities.

Efforts to transition to more "sustainable" cities require institutions to evolve. Brown [24,38] and Brown *et al*. [36] describe institutional development for sustainable urban water management. Common institutional barriers include fragmentation, poor political leadership, unproductive bureaucracies, and limited community participation in the planning process. Moreover, established physical and bureaucratic infrastructures combine with institutional memory to perpetuate existing systems and slow reforms [26,39–41]. Brown and Farrelly [42] note that most impediments to sustainable urban water management practices are institutional, not technical. The authors found a "paucity of targeted strategies for overcoming the stated institutional barriers," and many reform efforts concentrated on building institutional capacity for human resources rather than intra-organizational capabilities. Previously, Brown [24] identified that while existing knowledge and value systems have expanded to include new models for integrated urban water management, the associated regulatory and organizational structures have not advanced to match. In the United States, Heaney and Sansalone [43] note that water management activities are dispersed across numerous federal agencies and no federal water agency exists to effectively coordinate the needs of supply, environmental quality, and flood management. Adapting established institutions and practices to new goals poses significant challenges.

Characterizing Urban Stormwater Governance Structures

A variety of governance structures exist for managing stormwater. The authority, responsibility, and effectiveness of governance in a city often correspond to the extent of existing infrastructure and institutions.

For cities with substantial existing stormwater systems, governance is often well-developed and includes government agencies, industry groups, private entities, and community organizations. Such cities often have a hierarchical structure (local, regional, national), with each level contributing to management. City agencies and utilities are responsible for financing, operation, maintenance, and planning. National environmental agencies in many countries establish overall guidelines for stormwater quality and often provide at least some funding. State, provincial, or district authorities provide additional regulations, administrative support, and funding. For instance, in the US, requirements of the National Pollutant Discharge Elimination System (NPDES) permitting program are set by the federal Environmental Protection Agency (EPA), but the permitting process is usually administered by states. Technical requirements for system operation are set by scientific experts based on water quality and performance goals. Technical requirements combine with local, regional, and national economic and political constraints to establish high-level goals for system performance and cost. Requirements are communicated to policy-makers, administrators, and system managers, who develop standards and guidelines and determine operational policies. Local planning and maintenance personnel implement and adapt policies in the context of the local environment [44].

In addition to this formalized vertical structure, less-formal, horizontal planning may exist, which attempts to bridge gaps between relevant but compartmentalized responsibilities [24]. Horizontal relationships include inter-agency working groups, task forces, public participation schemes, and informal networks, which can bridge departments involved in civil engineering, environmental management, land-use planning, or finance. Horizontal planning arrangements are common sectors to balance institutional specialization and deficiencies.

At the local level, two basic organizational structures have traditionally maintained stormwater management responsibilities for established systems:

(1) Municipal government control, where separate city departments handle functions of water supply, wastewater treatment, and stormwater management;
(2) Mixed control where a utility (public or private) bears responsibility for water supply and treatment, while a municipal agency maintains responsibility for stormwater management as part of a larger environmental quality program or department.

Other agencies such as transportation or recreation departments may also maintain some responsibility for managing stormwater at particular sites.

Vienna, Austria, represents a Type 1 structure, with water, wastewater, and stormwater responsibilities all handled through municipal government branches. Water supply (MA 31), wastewater management (MA 30), and environmental protection (MA 22) are organized in separate departments, with vice-mayors overseeing collections of departments. In San Francisco, USA, much of the city has a combined sewer system, and the San Francisco Public Utility Commission (SFPUC), a department of the city and county, has "enterprises" for water, wastewater, and energy. The Wastewater Enterprise is the lead department for stormwater issues. Other agencies such as the metropolitan transit agencies and the Department of Recreation and Parks have smaller management responsibilities for areas in their control.

In Type 2 cities, responsibilities for stormwater and other water services are mixed between entities. In Copenhagen, Denmark, for instance, the utility Copenhagen Energy is responsible for water supply and wastewater treatment, while the Technical and Environmental Administration within the municipal government is responsible for environmental quality, to include surface stormwater runoff [45]. In Birmingham, UK, the city government manages surface stormwater in most areas. The national Environment Agency, however, has responsibility for surface water drainage for ordinary watercourses in city limits, as well as receiving water quality responsibilities in surface and ground water. The utility Severn Trent Water has responsibility for wastewater collection and conveyance [46]. In Los Angeles, USA, a stormwater management program was established in 1990 under the Bureau of Sanitation in the Department of Public Works, which also manages the city's wastewater. Program personnel interact with departments throughout the city, including the Mayor's Office, the City Council, outside regulatory agencies, and environmental groups [47]. Water supply is handled by the Department of Water and Power (LADWP), although LADWP also engages in stormwater capture to augment water supply [48]. Table 1 summarizes the two main governance structures for water management in industrialized cities, with associated stormwater management responsibilities.

Many private entities contribute to stormwater management and planning. Land developers construct localized sewer systems to meet municipal codes as part of land development. Commercial building and land build stormwater infrastructure to manage local runoff. Similarly, private or quasi-public entities with large tracts of land, such as hospitals or universities, often have dedicated energy and water departments. Industry groups such as the Water Environment Federation (WEF) and American Water Works Association (AWWA) disseminate research, best practices, and publications. Recently, entities not typically concerned with water are recognizing links between water, energy, and environmental quality. For instance, the US Green Building Council (USGBC), a non-profit organization that administers the Leadership in Energy and Environmental Design (LEED) criteria in the US, has begun including components related to water use and stormwater Best Management Practices as part of its certification and education programs [49].

Table 1. Organizational Structures for Stormwater Management in Industrialized Cities.

Water Management Responsibilities	Stormwater Management Responsibilities	Example Cities
Municipal Government Department (within same agency)	Managed by a department or several departments of a city	Vienna, Austria Tokyo, Japan San Francisco, CA, USA
Duties Split Between Municipal Agencies or between Government and Private Entities	Stormwater often managed by a separate city agency such as the Department of Environment	Washington, DC, USA New York, NY, USA Los Angeles, CA, USA Vancouver, BC, Canada Birmingham, UK Copenhagen, UK Sydney, Australia

Individual landowners influence local stormwater systems, especially water quality, through both short- and long-term decisions regarding land management, land cover, and pesticide use. Landowners make decisions to install infiltration swales or green roofs, or use fertilizers, pesticides, and other substances, which contaminate stormwater. Landscaping companies contribute to urban runoff through chemical treatments and debris cleanup. A variety of regulations, educational programs, and rebates incentivize private entities to undertake physical or behavioral changes, but awareness is often lacking. Finally, community groups such as neighborhood organizations or homeowners' associations (HOAs) provide coordinated planning and specific landscaping requirements, which can affect resident decisions. Some cities such as Washington, DC, USA, are developing incentive programs and municipal codes to reduce runoff pollution from private lands through mechanisms such as maximum allowable percent of impervious land cover or tax/permit systems [50].

Cities without major stormwater infrastructure typically also lack effective stormwater governance structures, both within and outside of municipal government. Residents have reduced reliability and increased spatial variability in managed system performance. Residents in such cities more often experience significant flooding even with routine rainfall [51], which is exacerbated by uncontrolled development in floodplains. Here, stormwater management is less likely to occur through central, hierarchical structures, and instead may rely on networks that link residents and community groups with city planners to manage rapid growth. When municipally-managed systems exist, they are often operated by agencies and departments with fewer regulatory requirements, less access to national or regional sources of funding, and less expertise. Implementation of more recent stormwater approaches such as green infrastructure is even further impeded by lack of knowledge. Municipal agencies in industrializing cities also are often more corrupt. High municipal borrowing costs combine with scarce expertise and funding to inhibit strategic planning, which leads to service deficiencies. Without municipal programs, a variety of private entities supply water services, sometimes at exorbitant rates. For wastewater management, private market efforts to fund sewerage and treatment are unlikely due to limited capital resources of residents. Residents with significant health, shelter, and nutritional needs are less likely to prioritize stormwater or wastewater management [52]. Some scholars argue that a lack of verifiable property rights inhibits residents from undertaking land and infrastructure improvements [53]. Despite these challenges, examples exist where communities organize to construct, operate, and maintain locally-managed sewer and stormwater systems [54,55]. Non-governmental organizations (NGOs) are also important in accessing expertise and capital for water projects.

In many poorer regions, local and national stormwater infrastructure efforts are augmented by expertise and capital from other nations. The World Bank and United Nations agencies often work with countries and cities to implement water supply and treatment projects. UN-Habitat, the UN agency responsible for housing, sanitation, and water supply programs, provides funding, research, and expertise to poorer nations seeking to upgrade infrastructure. National development agencies such as the Danish (DANIDA) and Swedish (SIDA) International Development Cooperation Agencies, or the UK Department for International Development (DFID) also provide access to capital and expertise for infrastructure improvements. In the Hanna Nassif neighborhood of Dar-es-Salaam Tanzania, a low-income neighborhood, a collection of organizations that included the United Nations Development Programme (UNDP) and the Ford Foundation completed a pilot project for community-based upgrading of slum areas. The program was broad, seeking to generate local employment while installing 600 miles of sewer drains. This pilot project was undertaken after other funding from the World Bank and the Tanzanian Ministry of Lands, Housing, and Urban Development had not materialized [56].

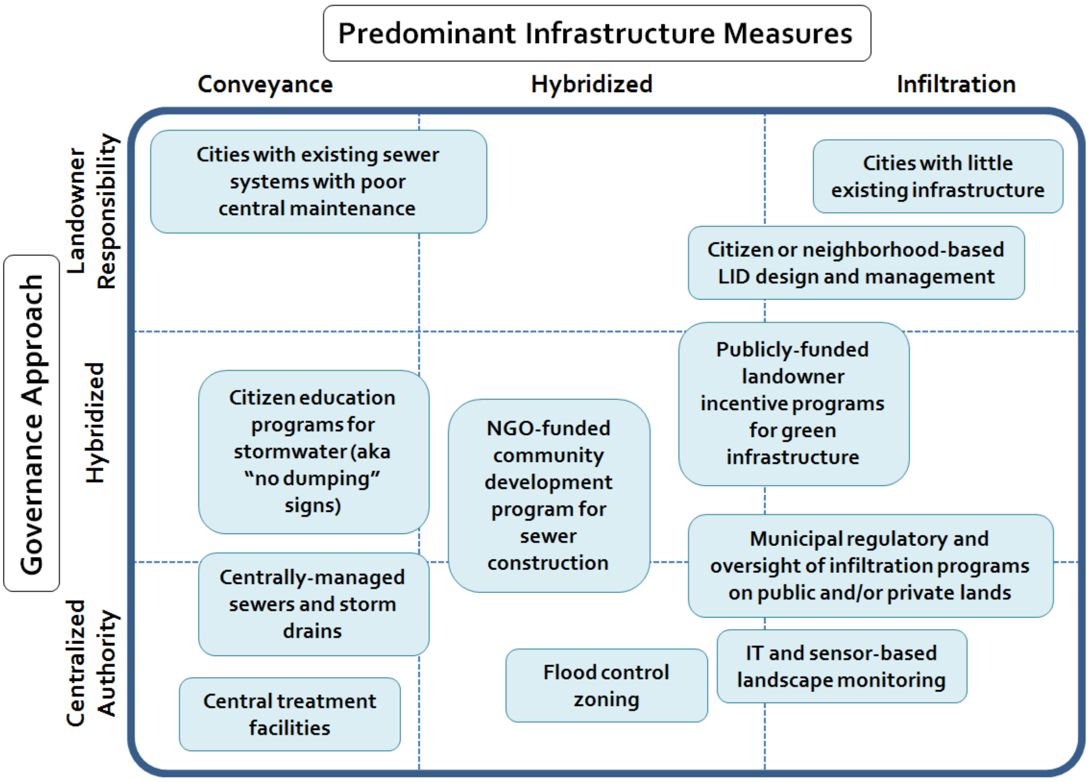
Even as industrializing cities expand infrastructure and develop more effective institutions, problems in management and capabilities still arise. For example, in the growing cities of China, municipal governments have invested in sewer system infrastructure as part of service enlargements for water and wastewater management [57]. Water governance in Beijing is primarily municipal, with layers of local- and national-level government organizations, including the Beijing Water Authority and district or county authorities. Management activities are constrained, however, by century-old infrastructure [58] and present-day managerial shortcomings. In 2012, massive flooding in Beijing caused damage and fatalities, prompting Beijing citizens to complain of inadequate management [59].

3. Hybridization in Stormwater Infrastructure and Governance

Stormwater management systems include structural measures that convey runoff and facilitate centralized treatment, as well as landscape approaches that promote infiltration on public or private property. Hybridized urban stormwater systems combine structural approaches (conveyance) with distributed landscape treatments (infiltration) to reduce runoff and improve water quality. While past management emphasized construction of conveyance infrastructure, urban landscapes have always provided some level of infiltration. Moving forward, agencies are recognizing the value of infiltration. This categorization is useful in describing approaches for physical management of urban runoff, but it does not describe potential differences in stormwater governance structures. Distributed infrastructure does not necessarily imply distributed management. In cities with established stormwater infrastructure, residents have traditionally not actively participated in management of either conveyance or infiltration infrastructure. This, however, may be changing in many cities.

A more nuanced conceptual model of future urban stormwater management encompasses both hybridized infrastructure and hybridized governance. Hybridized infrastructure combines conveyance and infiltration. Hybridized governance disperses management and monetary responsibilities between central experts and private landowners. An effective stormwater management system could theoretically combine hybridized infrastructure with central management, where agencies would be responsible for funding landscape treatments, administering landowner incentives, monitoring runoff and performing maintenance. A central authority could also dictate zoning requirements, acquire land, and conduct maintenance for conveyance and infiltration zones as part of flood management. Alternatively, a hybridized governance structure for distributed infrastructure may have a central authority managing structural measures, but provide incentives, education, or regulations to landowners who undertake autonomous actions. Figure 1 illustrates this model, with one axis representing a gradient of centralization in infrastructure and the other axis representing a gradient of centralization in management. Some examples for design and management are highlighted.

Figure 1. Conceptual model for hybridization in stormwater governance and infrastructure.



While cities are testing approaches that combine some hybridization in infrastructure (conveyance and infiltration), hybridization in governance (dispersal of construction and monitoring duties) remains less explored. In hybrid governance structures, difficult questions arise regarding the ability of system managers to assure proper operation when individual responsibility is prominent. Alternatively, many cities with poor existing infrastructure have by default distributed management and funding structures. Both governance and infrastructure change with time, for a century ago, many wealthy cities today lacked both structural measures and institutional oversight.

4. Drivers and Impediments for Hybrid Stormwater Systems

Cities are developing more hybridized stormwater designs for a variety of environmental, social, economic and public health reasons. Many cities must improve local surface water and groundwater quality to meet more stringent regulations, often by reducing pollution from typical urban runoff sources. Cities with combined sewer systems have an additional problem of reducing pollution from overflows during storms. Climate change scenarios are influencing urban planning for more flooding for coastal cities. Changing social attitudes are influencing stormwater approaches that integrate urban greening, energy conservation and private responsibility into infrastructure. Some cities project significant cost savings by promoting green infrastructure over traditional approaches [4]. For many rapidly growing cities, the opportunity to build new infrastructure means agencies can construct a combination of conveyance and landscape-based measures to reach more residents. As systems change with these realities, system governance also adapts. Table 2 summarizes goals priorities for urban stormwater management in cities with and without robust existing infrastructure.

Table 2. Urban stormwater management priorities in cities.

Goals	Cities with Established Stormwater Management Systems	Cities Lacking Established Stormwater Management Systems
Municipal Management Capabilities	● Meet budgetary requirements ● Satisfy municipal codes ● Meet standards for reliability and performance ● Align with larger regional growth plans to promote smart and sustainable growth ● Engage residents in management programs	● Expand services to keep pace with rapid growth in planned and unplanned areas ● Reduce corruption ● Increase system reliability ● Leverage training and knowledge transfer from external sources to develop internal expertise ● Reduce illegal system draws by residents while also servicing the population ● Secure capital for infrastructure improvements ● More comprehensive planning for long-term growth and urban development
Environment	● Satisfy local, regional and national environmental standards ● Improve local water quality ● Facilitate healthy ecosystems for recreation and economic benefits ● Minimize effects of Combined Sewer Outflows	● Reduce environmental impacts at little cost ● Improve quality of urban runoff ● Expand infrastructure capacity to consider supply, treatment and runoff
Public Health	● Prevent transmission of disease and infections ● Meet public health standards	● Improve system capabilities to reduce disease transmission and ensure clean water supplies ● Promote evacuation during floods
Social	● Enable citizen action and engagement ● Facilitate adoption of Best Management Practices by landowners ● Contribute to regional goals within constraints of social attitudes	● Enable local citizens access to clean water and municipal services at affordable prices ● Understand urban growth patterns and to meet infrastructure needs for industrialization

Despite enthusiasm for measures that promote infiltration, several economic and technical issues impede their immediate use. First, structural measures that promote conveyance are still important for flood protection in many cities, especially during large storms which overwhelm infiltration. Institutions with monetary and human capital investments in structural systems are unlikely to immediately abandon trusted structural measures. Second, maintenance and management for green infrastructure is poorly aligned with centralized bureaucracies and expertise, especially when located on private land. Agencies must disseminate knowledge more broadly and engage with residents, land owners and developers. Third, cities that promote flood protection and infiltration through zoning to prevent floodplain development must carefully manage urban growth, which is difficult for political and economic reasons. Fourth, many municipal water and environmental agencies may have insufficient regulatory authority to promote and monitor distributed systems. Integrated approaches for water and stormwater management are difficult when duties are dispersed across departments. Fifth, cities may have difficulty using existing funding mechanisms to fund green infrastructure development. Finally, the ability of distributed or hybridized infrastructure to improve water quality at lower costs than centralized systems has not been proven, and differences in climate, density and public communication are likely to influence effectiveness.

In principle, cities with stormwater functions in the same agency as other water services could undertake coordinated planning. In reality, bureaucratic partitions and funding streams exist even within agencies. Most stormwater infrastructure is funded through local sources such as general tax revenues, dedicated tax allocations, special assessments, land-use fees, or municipal bonds. Regional, state, territorial, or national sources may also be available [60]. More visionary regional stormwater programs are usually coordinated management entities, and both centralized and decentralized programs have proven successful [61]. As cities expand and managers recognize the multi-disciplinary nature of stormwater, some metropolitan areas are developing issue-oriented working groups that cut across traditional organizational borders to include both public and private entities. Cross-agency bodies often focus on watershed management, water conservation, or water quality. They can assist in developing long-term strategies, informational materials, and stormwater design guides tailored to the hydrology and landscape of a region. Formalized budget and policy structures are often necessary to allow agency employees to justify time and resources spent inter-agency planning processes and strong political support is important.

While cities with existing infrastructure seek to integrate "greener" approaches, cities lacking existing infrastructure face stark challenges to expand system capacity and reliability. A characteristic of industrializing cities is the presence of both formal and informal settlements. Formal settlements are planned areas with established zoning, infrastructure and municipal services supplied by governments. Informal settlements are areas where residents often lack official property rights [62]. These areas, which are places of both upward mobility and poverty, present planning challenges. Municipal planning processes, including zoning and infrastructure development, do not supply such residents with services for reasons of cost, zoning, capacity, or politics. Residents of these areas tend to have lower incomes, experience corruption in the absence of adequate governance, and migrate frequently between urban and rural areas. Over time, informal settlements may seek and gain formal recognition by municipalities, though governance and legal structures may still be inadequate [52,62–65].

Stormwater challenges in informal settlements result from geography, governance and economics. In many cases, squatters take over marginal land in floodplains or on mountainsides [52,66]. Many residents are unwilling or unable to pay for services due to economic status, low capital availability, or reluctance to engage with corrupt institutions. Instead, they may illegally connect to existing water and electricity systems, which degrades overall system performance. At the same time, public and private utility systems are under-funded and unreliable [67]. Many forms of corruption on the part of service providers exist, including: (1) inappropriate use of operational funds, (2) lack of transparency in operation budgets, (3) reliance on bribery to access services, and (4) inadequate record-keeping for payments to allow theft. Residents are left to take individual action for services that could be provided through municipal sources. Of these, stormwater management may be secondary to other needs for water and transportation.

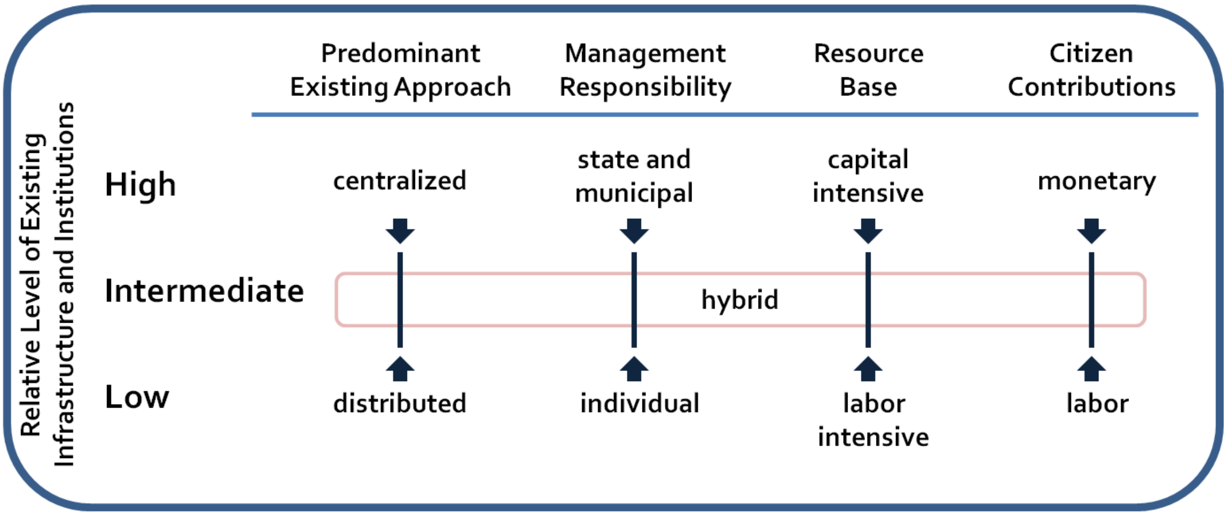
Without existing infrastructure and institutions, flood control and water quality become dangerous public safety risks. Residents cannot accrue sufficient capital to fund flood protection, stormwater conveyance, wastewater treatment and water supply. In addition, existing drainage canals are often used for trash, representing the failure of two public service sectors. Tucci [66] describes how in many Brazilian cities, urban development is based on a master plan that neglects effects of urbanization on drainage. Moreover, different stages of urban development reflect different types of pollutants, with early-stage construction likely to facilitate runoff polluted with larger sediment loads. Flood management problems stem from: (1) low investments in urban drainage facilities, (2) increases in peaks and frequency of floods due to inadequate system design and capacity, (3) a lack of drainage and other sanitation facilities, (4) a lack of technical expertise from engineers and architects, and (5) a lack of public participation [66]. Flood hazards are primarily from a lack of infrastructure owing to the above failures, occupation of the flood valley through informal urbanized settlements and lax flood zoning enforcement.

Contamination of water sources occurs from discharge of untreated sewage, discharge of stormwater with organic pollutants and metals, pollution of groundwater from industrial and domestic discharges (septic tanks, leaking pipes), deposits of urban solid waste, and land use that does not account for urbanization effects on the water system [66]. Often, system planning does not consider the higher population densities of informal settlements [68]. In humid regions, heavy regular rainfall can overwhelm stormwater infrastructure. Approaches adopted from established industrialized cities do not account for local climatic, ecological, and social aspects of poorer cities in humid and arid climates. Parkinson [69] argues that both structural and non-structural approaches are important for urban stormwater management in poorer cities. Traditional structural approaches may be inadequate for informal settlements, which have "narrow access routes, occupation of areas of risk, and lack of a precise definition of public and private space". Non-structural measures such as flood evacuation and warning systems, as well as public health and pollution control programs, can help mitigate impacts of regular and extreme stormwater processes more effectively in squatter areas.

5. Adapting Governance for Hybrid Infrastructure Systems

The level of existing infrastructure is useful in charting the trajectory of future stormwater system development in different cities. Management responsibilities, resource availability, citizen contributions and degree of centralization are related to the level of existing infrastructure. This creates an opportunity to explore the evolution of future stormwater infrastructure in different types of cities. Cities with extensive centralized systems are integrating conveyance and infiltration measures, and usually already have supporting financial and institutional infrastructure. To accomplish such integration, municipal agencies must decide to invest in greater oversight capabilities for distributed measures or enhanced public education campaigns to encourage residents to adopt more environmentally-friendly practices on private land. Cities without robust existing infrastructure often seek to create more hybridized systems by increasing centrally-managed capacity while also enhancing opportunities for private measures. Agencies in these cities must accrue capital for public works projects, fight corruption and build agency expertise. They must also engage residents to promote safe development consistent with floodplain management. Figure 2 illustrates a framework to understand how infrastructure and management characteristics relate to hybrid stormwater system development. While all cities are likely to move to more hybridized systems, understanding how different cities are hybridizing stormwater systems can help to organize more successful development of sustainable infrastructure.

Figure 2. Framework to understand relationships between existing infrastructure and social, economic and engineering characteristics.



Though cities are likely to pursue more hybridized approaches, hybridized governance structures will not necessarily follow. Cities face decisions to retain management centrally or disperse responsibilities by engaging residents. Cities with robust current systems generally have efficient and trusted institutions, which must reorganize funding and management duties based on decisions regarding resident engagement. Such agencies are likely to increase cross-disciplinary collaboration and resident outreach. At present, urban residents primarily provide monetary contributions through monthly payments, but leave operations and maintenance to central bureaucracies. As infiltration-based approaches increase, cities will likely transfer more responsibility to landowners, such as building and maintaining swales, green roofs, or other treatments on private property. Municipalities would still oversee public communication, incentive programs and monitoring capabilities. For cities without existing infrastructure, they must continue to develop robust governance structures that gain trust of residents. These residents will likely continue to bear significant responsibilities for managing stormwater through labor-intensive means in the absence of strong central oversight. As infrastructure and central governance increases, monetary contributions of residents, but this requires fundamental shifts in popular confidence in public institutions and capacity of residents to pay.

While cities have an opportunity to decide regarding hybridization in governance, economic and social realities are likely to increase hybridization in governance structures. Reduced public budgets in many industrialized cities are forcing agencies to engage residents to undertake private measures through both incentive and regulatory measures. Advocates of urban sustainability argue for more public participation in many aspects of urban life. In many wealthier cities, traditional centralized planning and operations models are beginning to incorporate broader agency and public participation. Many municipalities are bridging institutional gaps by establishing horizontal linkages through issue-focused working groups, programs and bodies, which bring together multidisciplinary personnel and cut across typical divisions of labor in local governments. Participants include managers from city departments, utility managers, federal or state/provincial representatives, non-governmental organizations and private landowners or businessmen and women. Water utility managers must continue engaging with other municipal government agencies that oversee transportation, building codes, planning and parks. Municipal agencies are also engaging private landowners through incentives, education programs and regulations. For all of these institutional changes, innovative approaches will become more popular as younger employees rise in their organizations.

Since most stormwater management decisions are local, cities, neighborhoods, and property owners are likely to experience the greatest shift in duties as cities incorporate distributed approaches, as shown in Table 3. System changes require alterations to budgets, regulatory responsibilities and public outreach. Bureaucratic institutions often resist changes to structure, responsibilities and funding. Agencies throughout government use cross-disciplinary working groups with responsibility for a particular issue to bridge traditional vertical responsibility chains. Negotiations among agencies delineate roles and responsibilities in the group. As groups become more established, and use resources, agencies legitimize the programs and develop formal mechanisms to justify resources dedicated to the cross-agency efforts. For stormwater, several cities have developed issue-based programs that cross vertical chains of responsibility to broaden public and private involvement in decision-making.

In growing poorer cities without existing infrastructure, city managers face challenges to accumulate capital resources, build institutional capabilities and increase public confidence simultaneously. This necessitates system development in a fast-changing urban landscape without established procedures for design review, procurement, construction and evaluation. Further, broad system goals are often not included in planning. Urban growth should be managed to recognize potential flood hazards in the context of urbanization trends. Informal settlements will persist, but urban planners can work with community organizations to conduct risk management actions that enhance the safety and security of residents. An opportunity exists to provide experience and knowledge from established systems as capital becomes available, though practitioners and funders should adapt (not copy) established models to incorporate the cultural and economic intricacies of a region. Greater access to information and communications technologies is likely to alter routine activities such as payments and service calls.

Funding is a significant challenge for all cities. In many Asian cities, rapid urban development is supported by growing capital reserves. System managers in these areas are already engaging experts to build systems rapidly. Industrialized nations in North America, Europe and Asia need to upgrade century-old systems. Managers must weigh funding for infrastructure against other goals in a time of shrinking public budgets. One idea for stormwater is a tax or assessment based on the percentage of impervious or highly landscaped land in a lot, which would incentivize landowners to increase infiltration and reduce watering needs. In developing nations of Africa or Asia, funding is typically inconsistent and interrupted by poor financial management and corruption. Taxes are hard to collect and municipalities have little affordable credit. Without coordinated, large-scale municipal planning, community groups, non-governmental organizations, and international donor organizations will continue to be important.

Table 3. Entities and associated responsibilities by scale of governance for centralized and hybrid stormwater system approaches.

Governance Level	Entities	Urban Stormwater Management Duties	
International	● UN Agencies ● Non-governmental organizations	● Funding ● Expertise ● Dissemination of information and implementation of new or best practices	
National	● Environmental agencies ● Flood management agencies ● Legislative bodies	● Establish national laws and standards ● Interpret laws for national regulatory targets ● Provide financing and incentives	
State/Territorial	● Water management agencies ● Environmental agencies	● Regulatory guidelines ● Financing options	
Regional	● Regional government councils ● Issue-focused, multi-agency entities	● Regional coordination ● Watershed management plans ● Facilitate working groups ● Share information across municipalities	
Municipality/ Utility	● Water utilities ● Environmental agencies ● Planning agencies ● Parks and recreation departments	**Centralized Management** ● Establish local stormwater codes ● Meet federal and state/territorial standards ● Fund infrastructure development ● Design, plan and operate infrastructure ● Review private plans for adherence to municipal codes	**Hybridized Management** ● Inter-agency planning processes ● Establish local stormwater codes ● Meet federal and state/territorial standards ● Fund infrastructure development ● Design, plan and operate infrastructure ● Review private plans for adherence to municipal codes ● Integrate cross-disciplinary knowledge
Neighborhood	● Homeowners' Associations (HOAs) ● Neighborhood Associations ● Local business and civic groups	**Centralized Management** ● Voluntary actions for landscaping and setting rules ● Information resource for homeowners regarding voluntary actions ● Pay taxes and fees	**Hybridized Management** ● Potential coordinating entities for neighborhood-scale management ● Responsible for meeting runoff guidelines ● Facilitate homeowner incentive programs ● Pay taxes and fees
Land Parcel	● Commercial and Residential Landowners	**Centralized Management** ● Pay taxes and fees ● Participate in voluntary incentive programs	**Hybridized Management** ● Pay taxes and fees ● Participate in voluntary or mandated incentive programs ● Meet land-use regulations ● Design landscape treatments ● Conduct long-term maintenance

Finally, municipal governments increasingly realize the importance of data and information technology (IT) in creating responsive bureaucracies and more efficient cities. Remote data collection can facilitate monitoring and reduce the need for distributed governance. In North America, the so-called Gang (or Group) of Seven, a collection of municipal IT leaders from Boston, Chicago, Los Angeles, New York, Philadelphia, San Francisco and Seattle, formed in 2010 to enhance coordination for developing technology solutions to urban management [70]. Data and metrics are critical for managing adaptable systems that meet multiple social and environmental goals, but many urban bureaucracies are ill-equipped to capture, analyze and disseminate available data. Cities are hotspots for data collection and analysis on private platforms such as mobile phones. Combining private data platforms with public sensor networks offers powerful opportunities to develop metrics for environmental monitoring. Environmental informatics is expanding rapidly through increased capabilities of remote sensing, field measurements and storage capacity [71]. More specifically, hydroinformatics is a growing discipline that studies the flow of information and transformation of knowledge to improve water resources management [72,73]. To take advantage of these opportunities, though, urban bureaucracies must gain greater internal expertise in data collection and analysis, while also facilitating open source application development. City technology systems are ill-equipped to promote these opportunities.

6. Reconsidering Governance Structures: The San Francisco Bay Area Example

San Francisco provides a relevant example to understand governance changes related to future stormwater systems. The San Francisco Bay Area has a total population of over 7 million people in nine counties and is dominated by San Francisco Estuary, where the Pacific Ocean meets the inland freshwater rivers. Together, the Bay Area counties surround and drain into the San Francisco Estuary, giving regional implications to stormwater management.

Management decisions regarding stormwater are made by national, state, and regional agencies, municipal agencies and utilities, neighborhoods, and landowners. Table 4 breaks down the entities and duties for each level of governance. Stormwater regulations are mandated by federal and state laws, including the Federal Water Pollution Control Act of 1972 (FWPCA), the Clean Water Act of 1977 (CWA) and the Safe Drinking Water Act of 1987 (SDWA). In California, water rights, water quality and pollution control are administered by the California State Water Resources Control Board (State Water Board). The State Water Board coordinates planning, permitting and enforcement with the San Francisco Bay Regional Water Quality Control Board (Bay Area Water Board), which administers and monitors compliance with federal and state laws, including issuance of NPDES permits for the area. Many planning documents outline goals for the region, including the Basin Plan [74] (Regional Water Board), the municipal-level Urban Water Management Plans (municipalities and utilities), the Bay Area Integrated Regional Water Management Plan (Bay Area Water Agencies), the San Francisco Sewer System Master Plan (SFPUC), the Watershed and Environmental Improvement Program Report (SFPUC) and the Better Street Plan (San Francisco Planning Department).

Table 4. Stormwater management in San Francisco: governance levels and duties.

Governance Level	Entities	Duties
National	• US Congress • US Environmental Protection Agency (EPA)	• Establish national laws and standards (Clean Water Act, Safe Drinking Water Act) • Delegate NPDES requirements
State/Territorial	• California State Water Resources Control Board	• Coordinate planning, permitting, and enforcement with SF Bay Regional Water Quality Control Board • Administer water rights and pollution control • Administer NPDES permits for combined and separate systems
	• California Department of Water Resources	• Facilitate Integrated Urban Water Management and Integrated Regional Water Management grants and goals • Administer stormwater flood management grants
Regional	• San Francisco Bay Regional Water Quality Control Board	• Regulate compliance with Clean Water Act and NPDES • Administer NPDES permits for municipalities • Facilitate working groups • Share information across municipalities
	• Association of Bay Area Governments (ABAG)	• Administer pooled revenue bond program for water and wastewater capital improvements • Facilitate inter-governmental coordination processes
	• Bay Area Clean Water Agencies (BACWA)	• Disseminate technical and regulatory information on regional issues and handle policy matters related to municipal wastewater agencies.
	• Bay Area Stormwater Management Agencies Association (BASMAA)	• Coordinate regional management and disseminate technical information for stormwater management. Most of the organizations members are part of the same NPDES MS4 permit
	• Regional watershed associations	• Coordinate planning and funding for watershed restoration and management activities
	• San Francisco Estuary Partnership and the SF Estuary Institute (SFEI)	• Regional body to coordinate planning and monitoring efforts to improve the health of the SF Estuary • SFEI conducts research and analysis for area watersheds
Municipality/Utility	• San Francisco Public Utilities Commission (SFPUC)	• Serve as lead agency for design, operations, and maintenance of water, wastewater, and stormwater systems in San Francisco • Maintain NPDES requirements and Stormwater Management Plan • Develop and carry out Sewer System Master Plan (SSMP) and Sewer System Improvement Program (SSIP), including the Urban Watershed Assessment • Administer the Urban Watershed Management Program as part of the Wastewater Enterprise, which houses interdisciplinary personnel for green infrastructure implementation • Review private stormwater plans for land parcels over 5000 ft^2
	• Other city agencies (transportation, parks, planning, public works and environment)	• Administer stormwater management actions for department lands • Participate in interagency working groups and programs to coordinate maintenance and planning • Maintain clean streets and sewer gutters (DPW) • Administer the Better Streets Plan (Planning Department)

Table 4. *Cont.*

Governance Level	Entities	Duties
Neighborhood	• Homeowners' Associations (HOAs) • Neighborhood Associations • Local business and civic groups	• Voluntary actions for landscaping and setting rules • Information resource for homeowners regarding voluntary actions • Collaborate with Urban Watershed Program to disseminate information • Pay taxes and fees
Land Parcel	• Commercial and Residential Land Owners	• Pay taxes and fees • Participate in voluntary incentive programs • Meet regulatory requirements for land parcels over 5000 ft^2 • Meet future regulatory requirements that may be instituted for homeowners or smaller land owners • Reduce environmentally-harmful activities such as pesticide use

In the city of San Francisco, the San Francisco Public Utilities Commission (SFPUC) is a municipal department responsible for water, wastewater and stormwater operations. SFPUC is divided into separate divisions and "enterprises," with enterprises for water supply, power generation and wastewater. The Wastewater Enterprise has primary responsibility for stormwater management. As with other North American cities, San Francisco has increased planning to integrate green infrastructure into existing land-use and drainage systems. In 2006, SFPUC led the drafting of the Sewer System Master Plan (SSMP) to establish long-term system goals and spending for the resulting Sewer System Improvement Program (SSIP). In addition to traditional investments to upgrade aging infrastructure, the document included LID and flood control as key goals [75,76]. In 2011, the agency began conducting an Urban Watershed Assessment to understand how to integrate green and grey infrastructure as part of the SSIP. The Urban Watershed Assessment process has reached out to all city agencies to define challenges, develop and evaluate alternatives, and provide recommendations by 2013. The Wastewater Enterprise also houses the Urban Watershed Management Program, which conducts various cross-sector planning and coordination activities related to permitting, enforcement, education and incentive programs for city land owners. This small group is an interdisciplinary mix of engineers, landscape architects and urban planners, with backgrounds in permitting, grassroots communications, stormwater design and environmental planning.

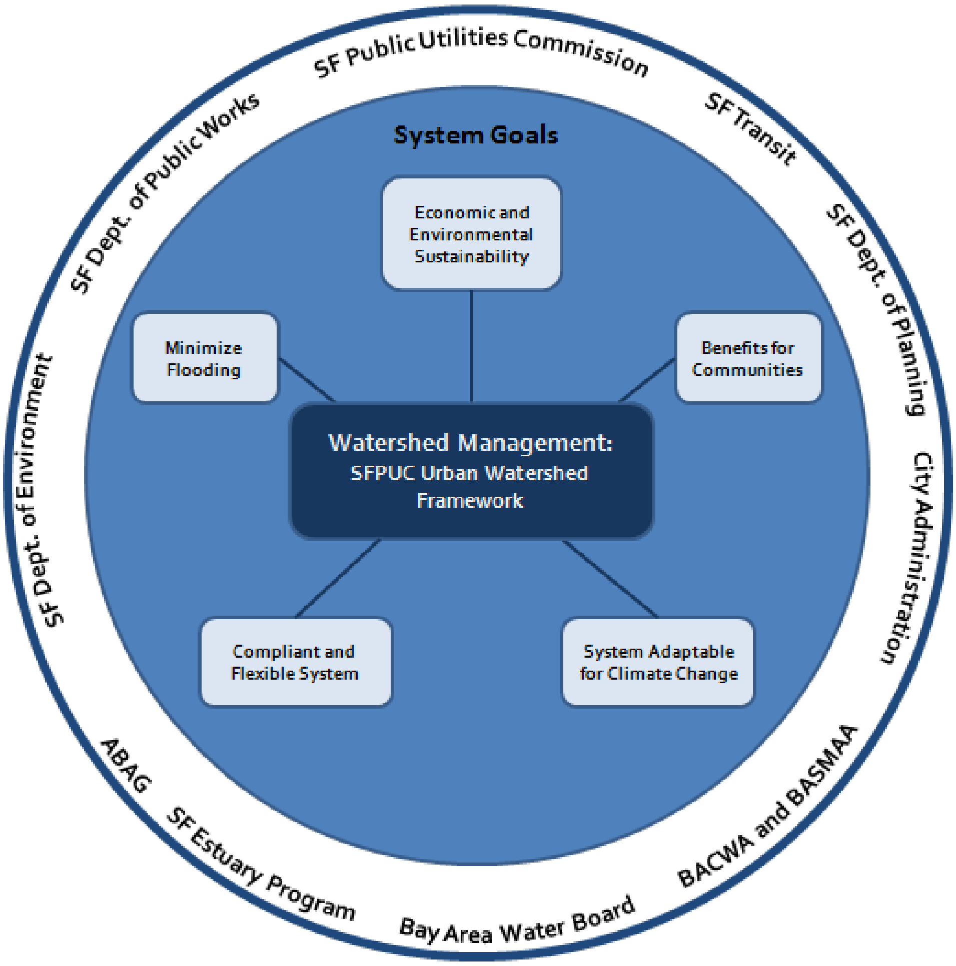
The activities of the Urban Watershed Management Program are part of a growing focus for the city on watershed-level activities. From 2007 to 2009, SFPUC conducted a series of planning charrettes that brought together experts to develop strategies and recommendations for green infrastructure implementation in various watersheds throughout the city [77]. SFPUC also completes an annual Watershed and Environmental Improvement Program Report to highlight activities for watershed preservation and restoration. These activities contributed to the recent release in 2012 of an Urban Watersheds Framework document, which provides guidance for future stormwater management in the city through integration of distributed (green) and centralized (grey) infrastructure. It describes the city's plan to evaluate expenditures for the Sewer System Improvement Program (SSIP), which is the implementation program for the Sewer System Master Plan.

The integrated nature of SFPUC's Urban Watershed Planning efforts requires that the agency collaborate with other city departments. Within the San Francisco municipal government, many agencies have stormwater management responsibilities. The Municipal Planning Department, which is responsible for urban planning and historic preservation, developed the Better Streets Plan in 2006 to assess opportunities to increase pedestrian safety, reduce pollution, enhance city beautification and promote smarter growth patterns. The region's municipal transit agencies, BART and San Francisco Municipal Transportation Agency (SFMTA), manage runoff in transit areas. The San Francisco Department of Environment leads programs in climate adaptation, renewable energy, energy efficiency, clean air, zero-waste, green building and more. The Department of Public Works maintains city infrastructure, including streets and public rights-of-way. Along with the elected leaders, this collection of agencies has roles in truly integrated water management and stormwater management. Ratified documents such as the Better Streets Plan and the Sewer System Master Plan provide the basis for collaboration activities, which are then codified through formal agreements between agencies to justify use of agency resources. Several agency and political leaders have pushed this approach, but the progressive attitude of city residents provides necessary popular motivation. Such interagency activities also require tools for coordination. The city has developed a central database for maintenance scheduling that most agencies use regularly to reduce duplicative or conflicting efforts in maintenance and construction.

The size of the San Francisco Bay Area and the cross-sector and multi-jurisdictional nature of stormwater quality necessitates coordinated stormwater management at several levels. New approaches for regional scale planning and green infrastructure integration are pushing governance changes. Figure 3 shows an integrated management scheme based on issue-focused governance. System goals are identified in the SFPUC Urban Watershed Framework. Rather than having the institutions at the center, the program and its goals lie at the heart of the approach. Activities such as SFPUC's Urban Watershed Management Program and Urban Watershed Assessment bring together professionals and managers focused on municipal issues but across multiple departments. Through urban watershed planning efforts, SFPUC facilitates interagency discussions that seek to align infrastructure development with social and environmental goals focused on cross-cutting issues. To date, the city agencies, especially SFPUC, have made significant progress to develop issue-focused plans for streets and watersheds that provide a forum for cooperation and break down traditional bureaucratic processes.

Even with these institutional connections, however, challenges still exist. Interagency coordination can consume time and resources, especially during early stages. Merging different bureaucratic procedures and funding streams is often difficult due to adopted policy and habits. Agencies must develop specific policy and funding mechanisms to justify early investments that can yield later results. In some instances, conflicting laws require significant time and effort to resolve. For instance, as SFPUC's Urban Watershed Management Program has worked to implement permeable paving projects, it has encountered regulations related to mobility for disabled persons. Working through this issue has required significant coordination with the Mayor's Office on Disability [78]. While tackling this issue can have long-term system benefits, it requires scarce time and resources. In addition, stormwater governance is influenced by legacies of past infrastructure and regulatory policies. For instance, areas outside of the downtown core often have different management issues because of different land use densities. From a scientific perspective, however, improving water quality in the San Francisco Estuary is a regional issue. The watershed framework provides the opportunity for more holistic management, but other necessary (yet potentially insufficient) components including strong leadership and funding streams.

Figure 3. Integrated framework for San Francisco stormwater management.



7. Conclusions

As urban stormwater systems evolve, cities have opportunities to pursue new approaches for design and governance to improve performance. Hybrid infrastructure for urban stormwater combines structural measures that facilitate conveyance with distributed measures that promote infiltration. Cities are increasingly combining both structural and distributed approaches into stormwater system designs. Hybrid governance structures for urban stormwater disperse management and financial responsibilities among central authorities, businesses and residents. Recognizing the distinction between hybrid infrastructure and governance is important, for they require different bureaucratic expertise. For instance, central management of hybridized infrastructure needs bureaucracies with more oversight capability, regulatory authority and information technology to enhance maintenance. Alternatively, distributed management of hybridized infrastructure needs bureaucracies to engage, educate and provide incentives to residents for maintenance and upkeep. While traditional stormwater approaches require centralized oversight and control, many sustainability promoters advocate more public participation and education for various sectors of urban life, including food, energy, water and transportation. To pursue sustainable infrastructure, cities must consider governance structures that balance the need to develop institutional expertise in new disciplines with the challenge of engaging busy residents to undertake behavioral changes.

Governance occurs within a decision landscape shaped by existing infrastructure, available capital, past political decisions, economics, public attitudes and changing social priorities. System changes challenge established procedures and funding streams. Most changes in governance are incremental, constrained by existing regulatory and legal authorities. For stormwater, local institutions, rather than national or international ones, require the most change to implement new management goals and conditions. Cities throughout the world must diversify employee skill sets and develop mechanisms to promote cross-department or cross-agency collaboration amongst engineering, environmental, financial and urban planning professionals. However, this expertise should be related to both goals for stormwater system operation as well as level of centralized or distributed authority. While sustainability advocates often (correctly) emphasize the benefits of enhanced citizen engagement, for an urban stormwater system, the benefits of public participation in, for instance, an urban greening program must be coordinated with the need for key system functions such as flood management and long-term maintenance costs. Such considerations do not rouse public excitement when the systems work well. State and national funding programs should support the ability of cities experiment with optimal mixes of hybrid infrastructure and public engagement.

The development of past urban infrastructure systems such as water distribution networks and sewers indicates that transitional periods are characterized by a period of hybridization [16]. For stormwater, however, hybrid systems may be the most viable long-term approach to balance performance and environmental goals. Cities are unlikely to ever use entirely distributed stormwater management infrastructure, as central services offer economies of scale and reliability, particularly for larger storms. While hybridization is increasing across many infrastructure sectors, including electricity, water, and communications, public engagement and increased personal responsibility are needed for successful designs. Current stormwater management institutions are not particularly effective at public engagement, but public interest in stormwater is often difficult to sustain. New technologies that enable more localized monitoring of distributed infrastructure will also be needed to assure system performance. The future of the sustainable city and its supporting infrastructure must consider both system designs and governance if 21st century cities will be truly environmentally-friendly.

Acknowledgements

The author thanks Jay Lund of the University of California, Davis, for insightful comments in multiple revisions of the article. The author also thanks Rachel Kraai of the San Francisco Public Utility Commission and Michael Connor of the East Bay Dischargers Association for their time and educational conversations. Finally, the author is grateful for the perceptive comments of three anonymous reviewers, which improved the article.

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