Old Solutions and New Problems:
On the Evolution of Urban Water Infrastructure and Environments

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Abstract

Urban water management strategies evolve with changes in technology, environmental conditions, development patterns, and social attitudes. At the same time, available options are constrained by prior decisions and existing infrastructure. In coming decades, urban water systems will face many challenges, including more stringent pollution regulations, water scarcity, increasing flood risks in coastal cities, and growing maintenance needs. Planners must design cost-effective systems that combine aging infrastructure with newly built components. Importantly, engineers and designers can learn from studies of infrastructure development in past eras, which also responded to rapid changes. Yet, earlier eras of urban water infrastructure expansion in industrialized cities emphasized different environmental priorities for habitat protection and water availability. Historical understanding can usefully inform the development of new analytical approaches and technologies to address urban water needs for the future.

This dissertation analyzes evolution in urban water infrastructure, focusing on innovation and resilience through interdisciplinary analysis and modeling. It explores change and growth in urban water supply and drainage systems, drawing on theory and techniques from water resources engineering, operations research, ecological "resilience" theory, urban environmental history, public policy analysis, and complex systems science. It uses several specific research and analysis approaches. First, it presents a historical survey of development in North American urban water infrastructure from 1800-2010, which identifies emerging trends in current urban water management. Second, it develops an illustrative model to optimize stormwater management allocations throughout an urban region based on economics, regulatory policies, and environmental characteristics. The model draws on theory and techniques from studies in urban geography, but incorporates contemporary understandings of development in complex urban systems. The model is applied to two regulatory cases: a target-based approach for runoff removal and a risk-based approach that minimizes expected damages. Third, the dissertation uses ecological and resilience theory concepts to analyze persistence and change in regional water distribution systems. Finally, it applies network science techniques to assess connectivity and resilience in a model of the California statewide water distribution system (CALVIN). Together, the chapters demonstrate novel theoretical and applied techniques to improve planning of future urban and regional water systems.

Results yield both quantitative and qualitative insights. Emerging trends in urban water management include: *Integration* across sectors of drinking water, wastewater, and stormwater*;* *Hybridization* in new technologies and management approaches*;* *Resilience* to address uncertainty*;* *Innovation* driven by individual cities*;* and *Complexity* in system design and analysis. The metropolitan-scale stormwater model revealed patterns in the cost-effective allocation of sewers, surface channels, landscape infiltration, and green infrastructure across a city. Current stormwater systems are largely explained by local climates and low-cost designs. In particular, land values drive optimal allocations and green infrastructure is effective in dense areas when cities avert land acquisition costs. At the regional scale, applying *ecological resilience* concepts to water management identifies thresholds in the supply and cost of water. After exceeding these thresholds, existing systems likely reorganize into new configurations. Finally, analyzing a large water system using network theory uncovers important system characteristics for connectivity and resilience in water infrastructure. The dissertation concludes with a summary of contributions for integrated planning and risk analysis in urban water resources.

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Finally, I am grateful for the many inspiring intellectual role models who use a passion for knowledge in creative ways to improve human and planetary conditions and, even better, make us laugh:

> *But I am into the intellectual thing, I went to college and studied the great philosophers, like So-Crates… and I studied Pla-do… You know, you learn the important things. If you are studying geology, which is all facts, as soon as you get out of school you forget it all because it's just numbers and things. But philosophy, you remember just enough to screw you up for the rest of your life.*
>
> - Steve Martin, *A Wild and Crazy Guy* (1978)

Mange Tak!

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Chapter 1

Introduction

> *The view from this bridge, mercifully concealed from mortals of small stature by a parapet as high as a man, is characteristic for the whole district. At the bottom flows, or rather stagnates, the Irk, a narrow, coal-black, foul-smelling stream full of debris and refuse, which it deposits on the shallower right bank. In dry weather, a long string of the most disgusting, blackish-green slime pools are left standing on this bank, from the depths of which bubbles miasmatic gas constantly arise and give forth a stench unendurable even on the bridge forty or fifty feet above the surface of the stream. Above the bridge are tanneries, bonemills, and gasworks, from which all drains and refuse find their way into the Irk, which receives further the contents of all the neighbouring sewers and privies.*
>
> - Friedrich Engels, "The Great Towns" in
> The Conditions of the Working Class in England (1845)

1 A Problem of Urban Water Infrastructure

Urban water infrastructure is sticky. It persists. In economics, variables are sticky when they resist change to broader trends, such as prices (Taylor 1980), wages (Harris & Todaro 1970), or information (Mankiw & Reis 2002). For many types of urban infrastructure, including water, electricity, transportation, buildings, and communication networks, stickiness describes the tendency of a current system to persist and influence future development. Urban infrastructure requires large investments in capital and expertise, creating an operational inertia that makes reformulating network structures difficult (Hughes 1993). Today's available choices are constrained by past decisions.

Path dependent systems of technology tend to perpetuate, driven by economies of scale inherent in maintaining and expanding existing configurations (David 1985, 1987; Liebowitz & Margolis 1995), while many social systems also persist as laws and policies become entrenched within organizations, governance systems, and disciplines (Kuhn 1962; Senge 1994). In urban infrastructure, economies of scale promote greater consumption to support steady revenue streams that fund current systems. Schott (2004) describes how past investments combine with the economics of system operations to affect decisions:

> The physical networking of the city by pipes and sewers was furthermore shadowed and duplicated by an evolving complex of institutional and legal regulations, which came to govern the relations between suppliers and consumers of these services. Since these services had- at least as compared with most industrial activities- rather high fixed costs, invested in the networks, in reservoirs, power stations and gasometers, and relatively low variable costs, their economic logic drove their managers to stimulate consumption by degressive tariffs; the more you consume, the less you pay per unit, thus favoring higher rates of consumption and consequently growth of resource use (Hughes 1993). With an agenda of sustainable development, this complex of material infrastructures, mental consumption patterns and economic and legal regulations today proves a major impediment to short-term changes (p. 522).

For urban water systems, this sticky infrastructure supplies fresh water and conveys by-products of urban life. In past centuries, when urban waste was primarily organic, the problem was the quantity and accumulation of waste. In today's industrial cities, infrastructure built to solve quantity problems conveys a host of chemical contaminants, including oil, pesticides, grease, pharmaceuticals, and heavy metals, which are difficult to separate from the organic wastes the systems were designed to carry (Schott 2004).

While built infrastructure is relatively static, other factors that influence economics and performance of urban infrastructure are more dynamic. For instance, population changes can affect geographic demand for services. Rapid urban expansion strains the ability of cities to provide adequate services, but rapid depopulation can leave shrinking cities with oversized, expensive, and aging infrastructure, as happened to many formerly industrial cities of North America in the mid- to late-twentieth century. In addition, seasonal climate variability produces droughts or floods that strain system operations. Emerging approaches to managing water resources emphasize "portfolios" of supply to provide flexibility under uncertainty (Hanak et al. 2011). Finally, technological advances can rapidly change infrastructure decisions. Before the eighteenth century, large capital investments for factories or public works were limited (Radkau 2008). During the industrial revolution, cities turned to the new field of engineering to devise technological solutions that promoted regional economic competitiveness and addressed public health concerns. New approaches to water treatment and conveyance, including slow sand filtration, chlorination, coagulation, sedimentation, pumping, and pipe materials changed urban water systems over only a half-century (Baker 1948). Yet, infrastructure systems and technologies last for decades within this dynamic set of regulatory, physical, environmental, and technological constraints. A central problem of urban water infrastructure is the tension between tendency towards long-term stasis and the need for advancements to respond to evolving challenges.

This dissertation seeks to understand and describe evolution in urban water infrastructure systems. Using both quantitative and qualitative methods, it demonstrates that analyzing change and addressing stickiness in urban water infrastructure is an interdisciplinary task. The dissertation incorporates interdisciplinary perspectives in many ways: it uses lessons of urban history to understand future trends; it employs operations research and risk analysis to analyze urban water systems; and it extends analysis techniques from complex system sciences to understand inherently complex infrastructure. Specifically, my goals are to:

1) Survey the history of urban water infrastructure development, including the social, economic, and technological factors that contributed to current systems, and draw conclusions regarding likely future trends (Chapter 2);
2) Create an illustrative model of metropolitan-scale stormwater management to identify where traditional (structural) and emerging (landscape-based) stormwater actions are cost effective in an urban region (Chapter 3);
3) Compare established, target-based regulatory methods for urban stormwater management with emerging, risk-based approaches using operations research techniques (Chapter 4);
4) Apply theoretical concepts and analysis techniques from resilience theory in ecology and network science to the study of structure and function of urban and regional water systems (Chapters 5 and 6); and
5) Understand how various economic, technological, social, and environmental factors influence stasis and change in urban water infrastructure.

The chapters address these goals using literature reviews in urban environmental history, operations research models and optimization of urban stormwater and regional water distribution systems, and network analysis for the California statewide water network. Further, they draw on many related fields, including urban economic development, city planning, urban ecology, complex systems science and resilience theory, water resource systems analysis, and risk analysis. This introductory chapter briefly introduces relevant literature in each field to inform the chapters that follow. It concludes with a description of the dissertation structure and specific methodologies found throughout.

2 Background: Industrial Cities and Beyond

Industrialization fueled and funded the modern city. Beginning in the Progressive Era in the U.S. (1890's-1920's), industrializing cities built centralized water infrastructure systems to improve public health and increase economic development (Chocat et al. 2001; Pincetl 2010; Melosi 2011). These systems were large public investments that brought water to users and conveyed wastes and storm runoff quickly to local sinks. They were designed to access readily available natural resources, maximize efficiency and economies of scale, and minimize citizen responsibilities. Cities balanced the need to acquire new water supplies from increasingly distant sources against the costs of pipelines and pumping (Lund 1990).

In the mid-twentieth century, governments responded to environmental contamination from the industrial, urbanized society, including organic wastes and chemical toxins, with increased regulations for treatment. Established methods of water treatment such as chlorine became public health and pollution concerns (Sedlak 2014). Today, cities further recognize challenges of resource scarcity and climatic variability (Hodson & Marvin 2009), which is driving many to seek more localized resources, pursue new technologies for treatment and reuse, exploit ecosystems services such as infiltration to manage runoff, and reconsider compartmentalized management within expert-based agencies. This evolution can be analyzed: 1) *descriptively*, by understanding history, regulations, and technological development, and 2) *quantitatively*, through integrated modeling and metrics of economic, engineering, and environmental factors.

2.1 Urban environments and ecology

Ecosystems in and around cities are complex zones where biological, chemical, and physical processes combine with human actions and built environments. In recent decades, urban ecology research has better characterized ecological processes in cities, including the distribution and abundance of organisms in built environments, as well as biogeochemical budgets (Pickett et al. 2011). Ecological processes such as nitrogen cycling, invasive and native species interactions, hydrologic cycles, and habitat selection all occur in both cities and less-disturbed areas (Pickett et al. 2008). Yet, in the "hybrid spaces" of cities (Walker 2010), these processes are especially influenced by human actions that affect soils, climate, water bodies, and air. The physical layout of cities results from both landscape and sub-surface features, including geology and watersheds, as well as resident behavior and political decision-making (Pickett et al. 2011).

Urban landscapes are heterogeneous. They consist of gradients, or changes in space, of land functions that range from heavily built areas to "natural" areas, and everything in between (Mumford 1956; Whittaker 1956; McDonnell & Pickett 1990). They also contain highly localized patches of impervious land, grass, parks, trees, and buildings that all affect runoff, nutrient cycling, habitat availability, and other ecological functions (Alberti et al. 2003; Cadenasso et al. 2007; Robinson 2011). Some aspects of urban environmental management, such as wildlife conservation (Adams 2005) or urban greening (McHarg 1969), predate contemporary urban ecology. But urban ecology research today incorporates greater scientific understanding and systematic thinking. Cities are one kind of a *social-ecological system*, which are coupled systems of human and natural components that interact in complex ways (Gunderson & Holling 2002; Berkes 2003; Redman et al. 2004). They are also complex adaptive systems with emergent properties (Jacobs 1961; Batty 2007; Marshall 2009).

Cities have a long reach. As concentrated areas of human social and economic activity, they require resource inputs beyond what can typically be provided by the immediate area. For centuries, cities have built infrastructure to facilitate flows of resources such as water, food, fuels, and commodities into and out of urban areas. The aqueducts of the Roman empire carried water long distances using rudimentary knowledge of physics to satisfy and clean cities (Frontinus 97AD). Land- and water-based transportation brought food and goods to early commercial centers. With industrialization, urban appetites for resources grew. Cities stretched far into the "hinterlands" (Tarr 2001) or the "countryside" (Swyngedouw 1997) to obtain critical materials. For today's industrial cities in an era of global commerce, the countryside is much broader, encompassing mountain lakes, distant oil fields, farms on other continents, and subterranean water and mineral reserves. The "footprints" of industrial cities are large (Rees 1992). By-products of urban life, including chemicals and air pollution, also travel long distances. Thus, cities have the potential to affect environmental processes within their boundaries, in nearby areas, and over far distances.

2.2 Complexity and evolution in systems and cities

Complex systems are dynamic and exhibit unexpected properties that emerge from the interactions of interconnected system components. For centuries, science studied problems with small numbers of variables, few relationships, and limited complexity. Complex systems science began with studies of unexpected order and non-linear dynamics in mathematics, physics, and chemistry (Nicolis & Prigogine 1989). One branch of complex systems, which studies self-organizing systems that use internal feedback to organize and self-regulate, dates back to early studies of cell biology and the writings of Immanuel Kant. Later, self-organization was applied to machines, which were "designed" by outside agents but capable of self-regulation (Keller 2008, 2009). In the social sciences, discussions of the emergent potential of complex systems are found in economics and sociology (Hayek 1955; Weaver 1958; Jacobs 1961). As computing power increased in the 1960's, scientists began analyzing more complex problems and classifying them. Some problems display *disorganized complexity,* where many erratic variables produce unpredictable results that can show order through statistical analysis. Others show *organized complexity.* Rather than the messy masses of confounding variables, studies of problems with organized complexity deciphered the interrelated network of possible explanatory factors that accurately describe emergent order (Weaver 1958).

Over decades, complex systems science techniques have been broadly applied across computer science, sociology, chemistry, economics, biology, meteorology, physics, medicine, and urban studies. Many types of complex systems are well-known. Chaos theory deals with complex systems that are highly non-linear and subject to initial conditions (Gleick 1987). Complex adaptive systems are dynamic networks with emergent, self-organizing properties driven by rules that govern the interactions of linked network components. A complex adaptive system "searches" possible configurations of adaptations to respond to changing environments. While not guaranteeing optimality, over time successive combinations of adaptations identify configurations that promote future success (Gell-Mann 1994). Overall system changes are driven by adaptations at both the individual and collective levels. These systems evolve, but conceptions of evolution differ across fields. Biological evolution describes natural selection and cumulative changes that result from mutations in populations over generations. Evolving notions of epigenetic processes describe how both mutations and environmental factors can affect gene transcription. Outside of biology, evolution is more broadly applied to include emergent changes in individuals, non-living objects, or behaviors that result from the collective interactions of individuals in a network or system. Marshall (2009) uses the examples of insect dwellings such as termite mounds and beehives to demonstrate how non-living objects also evolve and adapt over time, resulting from collective changes in physical traits (biological evolution) and behavior (interactions of individuals). In all complex evolutionary systems, changes are not driven by a central authority. In this view, living organisms, as well as non-living objects and systems, can evolve.

Cities function as evolutionary and complex adaptive systems. They are overlaying networks of interacting agents, objects, and processes that produce emergent and unexpected patterns of development (Jacobs 1961). The relationships between individuals shape the size and layout of urban areas. Physical structures and social processes may exhibit scaling properties governed by the interconnectedness of individuals and components (Bettencourt et al. 2007; Batty 2008), though the validity of universal characteristics is questioned (Clauset et al. 2009; Shalizi 2011). Specified rules that dictate the interactions of system actors can describe some emergent patterns in the growth, structure, and development of complex systems such as cities (Batty 2007), though humans recognizably retain individual decision-making capability. Feedback mechanisms and environmental changes drive behavioral adaptations of individuals (Forrester 1969). Yet, cities, and the sub-systems that comprise them, are hybridized systems of both planned order and organized complexity that can yield unpredictable results (Marshall 2009). Cities can also be highly influenced by the actions of relatively few individuals (Caro 1974). Thus, analyzing evolution in urban systems requires both knowledge of human history and an appreciation for science, ecology, complexity, and networks. This dissertation draws on a non-biological perspective of evolution, yet still inspired by the dynamics of biological evolution and ecological systems, to understand changes in urban environments and water systems, which are driven by the interacting networks of human actors and organizations, environmental processes, and technological components.

2.3 Systems perspectives for urban water

Urban water systems include many sub-systems and end-users. Water supply systems distribute water for residential, commercial, and industrial use. Many established, industrial cities import water from distant, cleaner sources to reduce treatment costs and contamination. Wastewater systems convey sewage and liquid wastes from homes, businesses, and factories. Stormwater (or rainwater) systems manage runoff from rainfall and irrigation to prevent flooding. Stormwater systems are increasingly required to manage not only quantity of runoff, but also quality. Runoff collects numerous contaminants found on streets, yards, and parking lots in the urban environment. Fire protection systems, closely related to water distribution, provide cities with on-demand, high-pressure water to combat fires. In early twentieth century cities, fire protection was often a critical component of water infrastructure projects, motivating greater centralization to protect buildings primarily constructed of wood (Melosi 2011). Traditionally, in industrialized cities, systems were managed in different departments or even different agencies. More recently, regulatory agencies, and cities themselves, are rethinking the compartmentalization of duties (Elmqvist et al. 2004; Brown & Farrelly 2009; Pincetl 2010). Integrating duties means changing institutions, which are path dependent.

In the U.S., systems perspectives for managing urban water emerged in the 1960's. Research developed new techniques to assess planning and development for water systems, including characterizing benefits and costs (Eckstein 1958), economics and pricing of water (Hirschleifer et al. 1960), water quality (Kneese & Bower 1968), design of water resources systems (Maass 1970), effects of urban water resources on cities (Jones 1971), and water balances in cities (McPherson 1973). In 1968, the American Society of Civil Engineers (ASCE) Urban Water Resources Research Council (UWRRC), outlined the components of an integrated view of urban water, including urban water uses, flood protection, groundwater recharge, recycling, and characterization of pollution sources (Heaney 2000). During this same period, state and federal regulations in the U.S. instituted water quality standards and provided funding for infrastructure improvements through the Federal Water Pollution Control Act Amendments of 1961, the Water Quality Act of 1965, and the Federal Water Pollution Control Act (FWPCA) Amendments of 1972. Discharges from point-sources (industrial and municipal outlets) were now regulated through the National Pollutant Discharge Elimination System (NPDES). Regulations combined with increasingly complex infrastructure systems to require new management approaches. Multi-objective optimization, river basin planning, and environmental modeling emerged as management tools (Rogers & Fiering 1986; Rogers 1993; Heaney 2000).

In the 1970's, the effects of environmental pollution and resource scarcity, especially crude oil, drove a surge of actions in industrialized countries worldwide to control pollution and reduce consumption (Ehrlich 1971; Club of Rome 1972; Adams 2009). Policies were driven by emerging attitudes in wealthy countries, which combined concerns over economic security, a desire to protect resources, and Malthusian conceptions of the limits of planetary ecosystems to support human life. In the 1980's, sustainability and life-cycle perspectives emerged as prominent themes for economic development, resource use, and lifestyles (Brundtland Commission 1987). Sustainability, with its multiple goals to promote economic, environmental, and social well-being, was rooted in a century of scientific research and environmentalism that increasingly emphasized "ecological managerialism" and technocratic approaches to ecosystems (Adams 2009). The rhetoric of sustainability has spread through public and private sectors worldwide.

Today, systematic, cross-disciplinary perspectives based in rational planning pervade policy goals for management of urban water infrastructure. Neimczynowicz (1999) described the main challenge for the future of urban hydrology to "organize cross-sectoral cooperation between multiple actors to introduce innovative technologies, management systems, and institutional arrangements which can meet multiple objectives." Integrated Urban Water Management (IUWM) describes approaches for managing water quality and quantity across the total chain of resource use in cities, including importation, treatment, waste removal, conveyance, recycling, and recharge (Rogers 1993; Heaney 2000; Mitchell 2006). Even more recently, Sustainable Urban Water Management (SUWM) meshes the economic, resource chain, and institutional perspectives of IUWM with the need to incorporate broader social participation in urban water planning to shift from the "linear, 'old-world'" view to an "adaptive, participatory, and integrated approach" (Brown & Farrelly 2009). Such policies integrate planning across disciplines, end-uses, and space, including individual parcels, blocks, neighborhoods, cities, and metropolitan regions (Heaney 2000). Technological innovation and institutional changes are important (Hering et al. 2013), but without understanding historical lessons and social attitudes, technological fixes may be inadequate (Bulkeley & Betsill 2005) or yield unforeseen consequences. For instance, large-scale development of urban water infrastructure in the industrialized world significantly increased consumptive water use (Gleick 2003), as utilities encouraged greater use to support revenue streams based on economies of scale (Hirschleifer et al. 1960) and resource exploitation in an expanding "water frontier" (Swyngedouw 1997). Technological solutions continue to emphasize goals that "decouple" the by-products of industrialization and economic growth from their environmental effects (Sörlin & Warde 2007).

2.4 Risk and uncertainty in planning

Water infrastructure in industrialized cities moderates environmental variability. For instance, while rainfall throughout much of the Western U.S. is intermittent and highly seasonal, large-scale water infrastructure projects capture, store, and release rainfall to move water in time and space. For decades, environmental management emphasized predictability, exemplified by Maximum Sustainable Yield (MSY) policies that sought the greatest allowable extraction of a renewable resource (i.e. trees or fish) from an area that would still sustain the population (Schaefer 1954). This view of managing environments fits with rational planning perspectives, where efficient and centralized procedures, enacted by expert-based institutions, enabled human exploitation of environmental resources at sustainable levels. It also fit with ecological notions of global stability, where ecosystems progressed through phases to reach stable states (Lewontin 1969; Sutherland 1974).

Beginning in the 1970's, ecology research questioned if ecosystems had globally-stable states (Sutherland 1974). Contemporary research recognizes that ecosystems are dynamic. Their structure and function can be altered by changes in state variables, driving variables, and other parameters (Holling 1973; Pickett et al. 1992; Ludwig et al. 1997). Equilibrium ecology was slowly replaced by a more nuanced view, where ecosystems may reach temporary equilibrium states but also transition to new states through disturbances (Sprugel 1991). Subsequently, a disequilibrium ecology emerged to describe how the "flux" of ecosystems results from external processes, internal relationships, feedback loops, and pervasive human actions (Pickett et al. 1994; Pickett 2013). Disturbances may originate from long-term environmental changes (climate change), short-term environmental effects (natural disasters), or human actions (Redman et al. 2004). Typical centralized approaches for managing environmental systems, infrastructure, manufacturing processes, and many other aspects of human societies, however, still emphasized predictable returns in stable systems (Hashimoto et al. 1982; Dovers & Handmer 1992; Holling 1996). In contrast, more complex approaches to describing and modeling systems, such as multi-objective analysis and system dynamics models, analyze systems by characterizing and quantifying the interrelated factors and feedback loops that drive function and behavior in many types of systems (Forrester 1969; Sterman 2000).

Today, habits are changing across many fields. In urban planning, for example, cities that built infrastructure to manage environmental events in the early twentieth century now recognize how uncertainty in climate and technology can affect cost-effective long-term planning. Operations research uses technical, rational approaches to solve complex problems and describe linkages between system components through statistics, optimization, and modeling. Increasingly, operations research employs risk-based approaches to incorporate uncertainty in planning and engineering (Stewart & Melchers 1997). Risk-based approaches are especially relevant for infrastructure that regulates environment resource use and disaster protection in cities, as climate change will likely alter the timing and frequency of both routine events that provide vital resources such as drinking water and catastrophic events that can bring wide destruction. Within flood protection planning, for example, research uses techniques such as probabilistic analysis to incorporate uncertainty (Davis et al. 1972; USACE 1996; Lund 2002; Zhu et al. 2007). The term *resilience* is commonly applied in many fields to describe approaches that recognize potential effects from uncertain events (Garbin 2007), including domestic security and critical infrastructure (McCarthy et al. 2007; National Infrastructure Advisory Council 2009), distributed energy systems (Bouffard & Kirschen 2008), and disaster-related research (Bruneau et al. 2003; Manyena 2006; Chang 2009). Uncertainty can also be characterized through complexity theory, where infrastructure systems are large networks of individual agents, whose interactions can generate emergent, unexpected properties (Geldof 1995).

The tension in systems between stability and transition, stickiness and change, and control and uncertainty are consistent, evolving themes for urban and natural resource management. Infrastructure systems in industrialized cities were designed to mediate variability, fuel economic gains, and improve public health. The successes were notable. Yet, today, resource constraints and climatic variability are forcing cities to diversify resource bases and examine ways to become more self-sufficient. If reconsidering evolution in human societies, one could posit that the era of managed stability is, in fact, an outlier in a human history pervaded by crises, regime shifts, disasters, and constant adaptation (Sörlin & Warde 2007).

3 Dissertation Structure

The chapters of the dissertation are divided into three parts, which are grouped by themes, methodologies, and scope.

Part I: History and Development of Urban Water Infrastructure

Part I explores historical, economic, technical, and policy literature related to urban infrastructure development through major eras of growth: industrialization, specialization, environmentalism, and systems integration. Chapter 2, *"Urban Water Infrastructure Development History (1800-2010): A Multi-disciplinary Review of Literature and Analysis of Future Trends",* summarizes the history of urban and water infrastructure. It draws on urban environmental history to understand the complex linkages in social attitudes, technology, and environmental processes through the era of industrialization in cities (1800-2000). It also identifies key emerging trends that inform future planning methods. The survey of research presents global examples but focuses on North American and Europe.

Part II: Some Models to Understand Evolution in Urban Stormwater Infrastructure

Part II presents theoretical models to understand and analyze how urban landscapes, economics, and environmental parameters affect the allocation stormwater infrastructure using infiltration and conveyance. The section presents an illustrative model to assess cost-effective allocations of stormwater actions in a metropolitan region. It specifically examines how managerial goals for drainage, treatment, maintenance, and green infrastructure affect allocations.

The chapters in Part II assess a metropolitan system using two different analytical approaches (Allison 1971). Chapter 3, "*Target-based Optimization of Stormwater Infrastructure across an Urban Region",* optimizes stormwater infrastructure throughout a metropolitan region to examine how climate, existing infrastructure, imperviousness, soil permeability, and land cost affect optimal allocations of infiltration and conveyance measures. The model uses several cases to illustrate relationships between land use, environmental parameters, construction and treatment costs, and the built environment. Chapter 4, "*Risk-based Optimization of Stormwater Infrastructure across an Urban Region",* uses the model from Chapter 3 to optimize stormwater allocations by minimizing expected flood damages and regulatory fines instead of meeting design targets. It simulates the evolving decisions cities face in developing stormwater infrastructure to prevent increasingly uncertain penalties.

The two chapters balance simplification and complexity in planning. For instance, the models draw on regional science research from the 1960's and 70's that simplified metropolitan regions to deliver general insights, while also recognizing more contemporary notions of urban development that describe diversity and heterogeneity in urban systems. The chapters contribute to literature by describing stormwater management at the metropolitan scale. They also establish how environmental parameters (hydrology and land cover/soil permeability) interact with engineered systems and economics. Modeled relationships, worked out through the simplified framework, could be applied to metropolitan regions using GIS tools with fine-scale data.

Part III: Emerging Approaches for Urban and Regional Water Management

Part III extends current research in network science and resilience theory from ecology to study urban and regional water resource systems. Chapter 5, "*Ecological Resilience and Water Resources",* reviews literature on the many conceptions of resilience for managing systems and presents an illustrative linear programming model of a statewide water distribution system that applies the concept of ecological resilience to water resources management. Chapter 6, "*Connectivity and Resilience in Water Resources Infrastructure: Metrics, Visualizations, and Scaling Laws in California",* analyzes the role of connectivity in water resource networks and links connectivity with resilience and efficiency through novel applications of network science. It illustrates how the statewide system of water distribution in California shows properties of complex, large-scale networks, and applies metrics and visualization techniques from network theory to analyze connectivity in the system using the CALVIN network model. Finally, chapter 7 presents overall conclusions.

4 Methods and Limitations

The dissertation draws on methodologies from several fields to analyze evolution in urban water infrastructure. Each of these methods has associated strengths and limitations, which are briefly described below.

Critical Reviews of Literature and Analysis

The dissertation includes critical reviews of historical, technical, and policy literature that provide background to understand water management in the context of urban development. Chapter 2 reviews literature on urban environmental history and uses it to identify insights for future trends. Other chapters (Chapters 3, 4, 5, and 6) provide literature reviews of relevant scientific and technical literature, including land cover and land use in urban regions, stormwater management, risk analysis in water resources, network science, and resilience theory in ecology. The reviews survey literature predominantly written by Western-trained scholars, which may impart a particular focus or interest to the resulting description.

Linear and Mixed-Integer Programming

Several chapters develop linear programming algorithms to analyze trade-offs and relationships among economic factors, environmental parameters, and urban structure. Linear programming algorithms are simple and adaptable approaches for analyzing systems using a defined objective. Optimization commonly identifies the "best" solution, but it can also function as a broader tool for systems analysis. Linear programming algorithms function best when modeling a limited set of parameters. Computational abilities, as well as the cognitive abilities of modelers, can be overtaxed. In addition, models are subject to assumptions and limitations of the formulations. Many models seek to minimize costs rather than maximize benefits. Model inputs are dictated by available data. Models of complex systems must simulate relationships between many variables and parameters. For models of systems with multiple objectives, several methods are available for analyzing trade-offs, but such formulations must compare objectives in standardized units or as changes in marginal relationships. Thus, while cities are adaptive collections of human and environmental processes, optimization models require simplifications. In addition, many critiques of optimization argue that such approaches are insufficient for analyzing dynamic, real-world systems.

One type of linear programming algorithm used in the analysis, mixed-integer programming, characterizes decision variables as discrete, binary choices. In this construct, the number of possible decision variables must remain small, as the set of possible solutions grows exponentially and is more difficult to limit than in linear constructs. Thus, the mixed-integer algorithm presented is limited in size and scope.

Stochastic Optimization and Risk Analysis

Stochastic optimization simulates how uncertain events, such as rainfall, affect best strategies. It calculates the sum of the probability-weighted individual events and the effects of those events to determine the best set of decisions that meet an objective. This approach can be useful when considering how climatic events affect cost and resource availability for urban infrastructure. Such approaches, while extending linear optimization, also have drawbacks. Stochastic models require parameter estimation regarding the likelihood of events, which is subject to assumptions and data availability. For climate events, the likelihood of very large, damaging storms can be particularly difficult to estimate. Gathering accurate data, especially in data-poor environments, is challenging. The procedure also requires estimation of the costs of planning actions and the damages associated with uncertain events. For damages to urban infrastructure, this is difficult. Finally, the algorithm presented does not consider timing of events. If two significant events that impose damages occur very close to each other, associated damages may change depending upon the situation.

Network Theory

Network theory draws on node-link structures to analyze connectivity, dispersal, and centrality in systems. It uses algebraic metrics to identify important nodes and links, as well as determine network-scale trends. As such, they are limited to the accuracy of the modeled network. Such networks take time and resources to develop from scratch, since the presence of a link between two nodes, as well as its strength, must be determined through fieldwork or data gathering. In addition, comparative analyses for networks are subject to limitations of knowledge of parameter ranges for different metrics. Since network analysis techniques are relatively new for water resources, the most informative approaches compare network structure and function between variants of the same network. Yet, applying network analysis to water resource networks does provide an opportunity to compare these networks to many other types of empirical and modeled networks for infrastructure and social interactions. This dissertation does both.

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Chapter 2

Urban Water Infrastructure Development in History (1800-2010)

> *Believing that another season of stomach complaint and gravel in the kidneys would do the citizens of New York City no irreparable harm, the Legislature took no action on the bill to charter the New York Water-Works Company during the 1824 session.*
>
> - Nelson Blake, in Water for the Cities (1956)

Abstract

This chapter examines the development of urban water infrastructure systems in North America since 1800 and assesses emerging trends in urban water management. The history of urban water systems may be categorized through successive eras with dominant themes, including acquisition of increasingly distant sources, drinking water and wastewater treatment, environmental regulations, and integration across sectors of urban water use. Many early systems began as private companies but transitioned to public-owned utilities through the nineteenth and early twentieth century to meet fire safety and public health needs. In the Progressive Era (1890-1920), many cities centralized management functions in administrative bureaucracies of trained experts in the hopes of reducing corruption and improving social welfare. After World War II (post-1945), municipalized systems expanded to reach an extended urban periphery of low-density suburbs, while cities of all sizes adopted basic treatment technologies. Later, environmentalist movements in the 1960's and 70's spurred state and federal mandates to reduce pollution from sewage overflows and institute public health requirements for drinking water. Today, a growing emphasis on sustainability goals, along with concerns over scarce water resources, is driving municipal water managers to promote self-sufficiency, coordination, and flexibility through "portfolios" of water supply options. Emerging trends in urban water management include: *Integration* across sectors of drinking water, wastewater, and stormwater*; Hybridization* in new technologies and management approaches*; Resilience* to address uncertainty*; Innovation* driven by individual cities*;* and *Complexity* in system design and analysis. Similar to previous eras, today's emerging trends respond to changing social attitudes, new technologies, available water resources, and climate variability. Urban environmental history grew out of research that studied development of U.S. urban infrastructure and provides important context for understanding evolution in urban water systems.

1 Introduction

Urban infrastructure systems, including electricity, water, transportation, and telecommunications, are critical arteries for daily life in cities. The sub-discipline of *urban environmental history* began with studies of infrastructure in North American cities and provides important context for understanding urban water systems. This chapter surveys and analyzes existing literature in urban environmental history to understand emerging trends in urban water management, which can help inform engineering and design.

As industrial cities developed through the nineteenth and twentieth century, they relied on innovations in technology and management to reduce disease rates, acquire resources, and promote mobility. Centralization in design and operation of urban infrastructure accelerated through the industrial era, fueled by economies of scale and adherence to rational planning (Mumford 1961; Tarr 1984; Hughes 1993). At first, nearby natural resource stocks allowed cities to meet expanding demands for water and electricity. In time, however, cities faced significant financial, public health, and nuisance burdens from pollutants and by-products of urban life (Tarr et al. 1984; Melosi 2001). Today, many cities are rethinking industrial-era approaches to building and maintaining infrastructure within the context of sustainability goals (Calthorpe 1993; Pincetl 2010).

Even as cities consider new strategies, they are constrained by past choices. *Path dependence* (David 1985; Liebowitz & Margolis 1995), or the tendency for past investments and actions to shape future strategies, is strong in urban infrastructure (Hughes 1993; Schott 2004). Cities create and then retain bureaucratic and physical infrastructures to manage centralized systems, and prior investments influence the economics of operations. Yet, cities must examine strategies that update current systems to decrease energy and water consumption, improve environmental restoration, and promote amenities such as urban greening. Cities are exploring many approaches to meet these challenges, including developing hybrid systems with centralized and distributed measures, incorporating climatic and resource uncertainty into planning, and shifting from expert-based management to include more citizen involvement.

This chapter traces development of urban water infrastructure in North American through eras, including early public and private water delivery systems, drinking water treatment, wastewater treatment, pollution and environmental regulations, scarcity, and emerging approaches. It discusses key themes during this evolution, including causes of centralization in design and management, the role of social trends such as suburbanization and urban revitalization, and the role of *path dependence* in urban infrastructure. It concludes by extending current literature to discuss trends in urban water systems, including hybrid designs of centralized and distributed measures, resilience, citizen involvement, and greater emphasis on local reliance for water supply.

2 Growth in cities: Economics, technology, and scaling

Cities embody promise and perils for human societies. While cities facilitate economic activity and often reduce per capita resource use, they concentrate environmental degradation and social problems (Rees 1992; Batty 2008; Glaeser & Kahn 2008; Bettencourt & West 2010). Infrastructure and natural resources are intimately linked to urban growth and technological innovation. Humans began assembling in large cities nearly 12,000 years ago in Mesopotamia. With agriculture, urban settlements grew and promoted commerce, wealth accumulation, and social exchange. In the millennia before 0 A.D., urban settlements were concentrated around the Mediterranean Sea, in Northern Africa, and in Asia. As human populations grew through 1000 A.D., cities in southern Europe (Cordova, Spain), Northern Africa (Cairo, Egypt), the Middle East (Istanbul, Turkey and Baghdad, Iraq), and East Asia (Kaifeng, China and Kyoto, Japan) were prominent, with populations ranging between 125,000 and 450,000 residents (Chandler 1987). By 1500, major populations had shifted to East Asia with the growth of the dominant Chinese dynasties. The onset of industrialization created global population centers in London, Paris, New York City, and Tokyo.

This urban growth in industrialized countries was correlated with rapid exploitation of natural resources and a growing focus on economic specialization of production, codified by Adam Smith (1776) and others. Centralized production could produce economies of scale, whereby increases in productivity resulted in greater wealth for the same input. Companies, governments, and societies sought to maximize efficiency through centralized management and workflow analysis, exemplified by the philosophies of Frederick Winslow Taylor (1911) and Louis Brandeis (Drury 1915). Centralized management was adopted by many cities to administer an expanding suite of public services and improve competitiveness for attracting new migrants (Melosi 2011). Later in the twentieth century, as economic researchers sought to understand why cities were dynamic economic centers, economics identified innovation as an endogenous driver of economic growth, and innovations result from capital and knowledge agglomerations in cities (Lucas 1988; Romer 1990; Krugman 1991). While cities amplify some economic and social benefits, they also generate externalities of disease, pollution, and increased potential for crime. Technological and bureaucratic innovations grew rapidly through the industrial era to solve these urbanization challenges, driven by a growing class of engineering and management experts.

New technologies have always been critical in shaping urban development. Sewers, steel for high-rise buildings, power distribution systems, and concrete are a few examples of innovations that have greatly influenced the design and function of cities. In the early twentieth century, cities created en masse a collection of water, electricity, transportation, and telecommunications technologies that revolutionized urban life. Today, innovations in transportation, energy, and water, combined with increased data collection and analytics, could again transform cities in a new era of global population expansion in rapidly industrializing (and urbanizing) countries. At the same time, projected urban growth will stress these systems and climatic variability poses new economic threats. Cities throughout the world face critical challenges from disease, habitat destruction, pollution, and waste disposal. Technology alone will likely not address the environmental and economic challenges of complex social-technological-ecological systems in cities. Institutions, regulations, social attitudes, and environments all influence urban prosperity.

3 Urban Environmental History: Perspectives for Infrastructure

Urban environmental history merges analysis of urban ecosystem processes that shape and fuel life in cities with the social and technological factors that determine resource use and environmental effects of urbanization. The field began predominantly in North America. Its early scholars, which had been publishing research on the intersection of urban development, technology, infrastructure, and resources for several decades, began arguing for a place for cities in the new discipline of environmental history. Melosi (2001) defined urban environmental history as "the study of the natural history of the city with the history of the city building process and the possible intersections between the two." Scholars in urban planning, such as Patrick Geddes, Peter Hall, or Lewis Mumford, had previously considered aspects of urbanization and ecosystems with an eye towards the role of environmental resources in city planning. Yet, this was human-driven. How environments influenced cities was still largely an open question. As the effects of urbanization became apparent, including pollution, sprawl, loss of habitat, and resource exploitation, technical and design professionals faced challenging questions of urban sustainability, while sociologists contemplated how best to describe and study linked urban and ecological systems.

Why is urban environmental history important in studying urban infrastructure development? Its value lies in describing the multi-disciplinary factors that shape relationships between technological and environmental systems in cities. Infrastructure provides vital services for residents by distributing resources that, in today's world, are ecologically constrained. Infrastructure manages the needs and by-products of urban life. In cities of high population densities in the industrial age, environmental degradation must be mitigated through both improvements to technology and actions that change social and organization behavior. Urban environmental history studies both of these and can provide insights for the future of urban development.

3.1 Key themes in urban environmental history

Joel Tarr, one of the notable researchers in the field, outlined five key themes (Table 1) for urban environmental history (Tarr 2001). First, urban environmental history studies the impacts of built environments in cities on the surrounding environments. Built environments are characterized by Tarr, Thomas Hughes, and others as networks of infrastructures that are critical to society but self-reinforcing through large investments in capital and expertise.

Second, urban environmental history studies societal responses to environmental problems and efforts to alleviate these problems. Infrastructure, regulations, and technologies are all important components in a complex web of drivers and feedbacks.

Third, urban environmental history explores how natural environments affect city life. This theme is captured by William Cronon in his seminal work, *Nature's Metropolis,* which describes how cities both change surrounding ecosystems and exist within environmental constraints.

Fourth, urban environmental history studies the relationship between cities and an ever-expanding hinterland, or what Swyngedouw (1997) might call the "countryside." The hinterland is the vast expanse of non-urbanized areas that supply critical resources necessary for continued economic growth and expansion.

Table 1: Key Themes in Urban Environmental History (Tarr 2001)

Theme	Examples
Impacts of built environments in cities on the surrounding environments	- Contaminant loads in local watersheds from factories - Urban air pollution from automobile exhaust - Resource consumption through networks of infrastructure
Societal responses to environmental problems and efforts to alleviate these problems	- Regulations for water and air emissions - Urban zoning laws to prevent settlement in areas prone to flood or pollution risks - Environmental remediation programs in cities
Effects of natural environments on city life	- Influence of local geography on transportation and buildings in a city - Effects of hydrology on urban policies for water infrastructure investments
Relationship between cities and an ever-expanding hinterland	- Relationship between urban planning goals for dense cities vs. suburbs over eras of city life - Infrastructure built to deliver far-reaching resources, such as mountain lakes, to cities
Roles that gender, class, and race play in shaping urban environments	- Zoning and real estate titles for expanding cities based on income - Development and establishment of informal settlements - Role of women in economies and social life of industrializing cities - Use of gender as a tool in urban development debates

Finally, urban environmental history often studies how gender, class, and race shape urban environments. Disparities in the allocation of environmental resources within cities are an important component of power relations and equity. This chapter draws primarily on the first four themes to understand the development of urban infrastructure in the context of a multi-disciplinary history incorporating urban environments.

3.1.1 Exploring the themes

As noted, many early studies in urban environmental history began by analyzing of the development of urban infrastructure. Initially, environmental conditions dictated infrastructure networks. Cities close to freshwater had easy access for transportation and water supply. With capital accumulation and technology, urban leaders contracted the new engineers of Europe and America to build infrastructure that promoted cities in a quest for growth capable of transcending environmental constraints. Los Angeles, for example, was transformed from a semi-arid valley with groundwater resources into a vast agricultural and urban metropolis through large infrastructure projects, capital investments, underhand deals, and healthy disregard for environmental constraints (Reisner 1993). These areas were ripe for exploitation and cultivation through an expanding "water frontier" (Swyngedouw 1997). More broadly, cities throughout the world built networks to funnel resources in and remove wastes from the growing urban economic engines.

Smaller cities can rely on local sources of food, building materials, water, and energy. With growth and density, local resources become strained. Cities develop social and technological solutions to exploit new reserves of natural resources and expel the by-products of urban life. Tarr aptly calls this the "search for the ultimate sink." With density, growth, and industrialization, however, the by-products became more numerous and toxic. Local water and air became contaminated. Industrial cities throughout the world sought new technologies and social institutions to combat disease and improve health. Networks of infrastructure were central for water supply, sanitation and wastewater, and electricity (Hughes 1993; Melosi 2000; Tarr 2001; Schott 2004).

The networks were sometimes too efficient in removing wastes from cities and delivering them elsewhere. Subsequent regulations required cities to reduce pollution to local environmental sources, exemplified in the U.S. through the Clean Air and Clean Water Acts. Regulations are social responses to environmental problems and fall under Tarr's second theme for urban environmental history: societal actions to alleviate urban problems. Beyond regulations, many social responses in recent decades seek to reduce environmental effects of cities. But they can also work in reverse. For instance, water consumption in industrialized societies increased following large-scale deliveries of treated water. Numbers vary, but the U.S. and Canada have high rates of per capita consumption (> 1000 liters/capita/year), while countries in Western Europe vary with moderate usage (approximately 300-900 liters/capita/year) (Gleick 2003). Australia, which has suffered from severe drought in the past decade, cut per capita residential water use by nearly 35 percent between 2000 and 2009 (83 gallons per day to 54 gallons per day) through policies such as restrictions on outdoor water use, water-efficient household appliances, and water pricing (Cahill & Lund 2013). Meanwhile, many countries in Africa, where the majority of residents have little or no access to centrally-treated, water have much lower water use rates. Thus, while addressing urban sanitation problems, urban water systems spurred some societal responses that strained water resources.

Industrialized cities require continued access to new resources. This speaks to Tarr's fourth theme for urban environmental history: the relationship between cities and the hinterlands. Cities transform their core areas and surrounding environments through a constant drive to acquire resources for growth. Water, food, energy, and materials come from many places, including underground aquifers, distant oil reservoirs, farmlands on other continents, or local suburbs. Cities must seek new sources of such necessities in the hinterlands to meet challenges of density and scale, while also driving consumption and growth. Despite calls for new knowledge-based economies, cities still consume natural resources. A rich literature has also examined the processes of suburbanization, urban-rural gradients, and other themes that link cities with surrounding lands (Jackson 1987; Hall 1988; Garreau 1992; Duany 2010).

Tarr's final theme in urban environmental history, studying the roles that gender, class, and race play in shaping urban environments, is perhaps the most diverse. Cities influence and are influenced by surrounding ecosystems, but social processes drive urban life. Decisions that affect the distribution of environmental resources among urban residents are political and affected by social attitudes and economies.

Inequality in the distribution of urban environmental resources occurs in several forms. First, poorer residents often have reduced access to centralized services such as energy and clean water. This is especially true in the context of industrializing cities, where limited capital exists to fill large investment needs. Built infrastructure serves those with strong political connections. Swyngedouw (1997) uses the example of Guayaquil, Ecuador, to illustrate how global processes influenced the development of water infrastructure over decades. Poorer residents were consistently underrepresented in planning and distribution. Second, environmental risk is not equally distributed among urban residents. Marginalized groups, such as minorities and those of low-income, often locate in lower-rent areas with greater risks to natural or human-made hazards. For instance, low-income neighborhoods in industrializing cities inhabit low-value land, often with greater environmental hazards such as floods or untreated sewer outflows. In particular, many informal settlements grow in seasonal floodplains because the high-risk land is unoccupied and governments fail to build flood control infrastructure. Third, marginalized groups are subject to discrimination and underrepresentation in redevelopment policies. In industrialized cities, the current trends towards rejuvenation of core city neighborhoods often results in gentrification. Long-time residents in older minority neighborhoods are displaced in favor of wealthier, though potentially diverse, young professionals. In industrializing cities, the move towards market-driven growth uses politics to drive land redevelopment that benefits powerful interests while displacing marginalized residents (Neuwirth 2006; Doshi 2013).

3.2 Path dependence, urban metabolism, and security

Schott (2004) identifies two important, cross-cutting themes in urban environmental history. First, scholars are increasingly interested in resource flows into and out of cities: the urban metabolism. Historians describe this in primarily qualitative terms, while recent work in urban ecology, systems engineering, and regional planning has developed methods to quantify resource flows. The ecological footprint concept is increasingly applied to measure flows (Rees 1992; Rees & Wackernagel 1994; Rees et al. 1995). Urban ecological footprints estimate resource demands in an urban region, linking them with carrying capacity and expanding the recognized extent of ecological systems that support urban life. Cities are not self-sufficient or self-sustaining, but decreasing their footprints can help regional sustainability efforts. Urban environmental historians place this concept of urban metabolism with earlier research in human ecology.

Second, Schott describes the importance of path dependence in cities. Technological and social systems require investments. Cities continue using existing systems because they are cheaper, since costs are paid and expertise is acquired. Path dependence can impede new development in large public systems. Infrastructure requires large capital investments and lasts for decades (Hughes 1993). Sometimes, infrastructure is built without accurate scientific and technical knowledge but continues to operate. Sewer systems were built underground based on mistaken public health theories (miasma theory) that believed disease was transmitted through air (Tarr et al. 1984).

While the goal of industrialized cities to transcend environmental constraints was arguably successful for a time, new challenges are evident. Today, cities increasingly recognize resource scarcity and climatic variability. Hodson and Marvin (2009) examine how cities are currently preoccupied with reinventing policies, infrastructure networks, and social norms to promote continued growth in the face of uncertain access to resources. They use the term *Urban Ecological Security* to describe actions global cities take to secure future livelihoods. Security concerns have moved beyond terrorism to recognize threats from climate change, water scarcity, more expensive oil, and other natural disasters. Cities are forming new types of knowledge networks, created in a spirit of desperate cooperation and healthy competition, to develop policies of Secure Urbanism and Resilient Infrastructure (SURI). SURI strategies aim to de-couple cities from increasingly uncertain regional and national resource networks, in favor of high-tech localized resource exploitation. For example, policy goals in Southern California emphasize water self-sufficiency, driven by uncertain statewide supplies and facilitated by reduced consumption, improved technology for reuse, and new strategies to capture runoff (LADWP 2010). At the metropolitan level, secure urbanism strategies seem to be effective policy rhetoric but more difficult to enact. Cities have always relied on outside resources to sustain life. Self-sufficiency goals may be more realistic for smaller, affluent communities such as Santa Monica, which has a stated policy goal of self-sufficiency by 2020 (City of Santa Monica 2011).

4 Eras of Infrastructure Development in North American Cities

Infrastructure makes up critical physical and technological systems in the built environment, or the “sinews” of the city (Tarr 1984). With industrialization in Europe and North America, cities developed infrastructure that utilized new energy sources to facilitate commerce and exploit natural resources. Over several centuries, municipalities increasingly undertook central roles in financing, planning, constructing, and promoting infrastructure systems. The competition between cities for economic prowess and innovative infrastructure was often fierce. In eras of rapid expansion, new infrastructure supported population growth and addressed stark challenges from increased population density and disease. Private service delivery was sometimes profitable at limited scales, but as capital needs grew, cities were better able to mobilize financing for larger projects (Melosi 2011).

In recent centuries, urban infrastructure development can be understood according to patterns in planning, population density, capital investment, and mobility. Table 2 classifies eras of major urban infrastructure growth, describes the characteristics of each era, and indicates major developments in water infrastructure.

The sections below integrate the classification of urban development eras with corresponding periods of urban design and planning, focusing on North America and Europe. Section 4 below describes eras of development in infrastructure generally and Section 5 identifies related eras of urban water infrastructure.

Table 2: Major Eras of Urban Infrastructure Growth and Developments in Urban Water

Period	Dates	General Characteristics	Water Infrastructure
Walking Cities	1800-1860	• Founding infrastructure and development patterns • Location near water and resources • State and local financing	• Decentralized management (pools, cisterns, wells) with growing municipal interest and consolidation • Use and pollute local water sources • Tap local water first, then reach out to nearby rivers • Early drinking water treatment • Sewage problems and solutions • Rise of public health engineering • First municipal water and sewer systems
Industrial growth & development of core urban areas	1860-1910	• Cities establish core systems • Expansion of consulting engineers • Landscape beautification • Rapid population expansion	
Automobile culture	1910-1950	• New models of industry and transit • Federal expansion • Rapid highway construction • Onset of suburban expansion	• Centralization and regionalization of water supply duties • Increasing pollution • Adoption of filtration and chlorine • New Deal expansion of federal spending for urban water • Dispersion of management across agencies • Expansion of federal legislation • Point-source pollution controls • Realization of water availability problems
Radial expansion & environmentalism	1950-1987	• Municipalities + central planning • Development of outer rings • Shrinking urban centers • Growing environmental concerns	
Revitalization and longevity	1987-present	• Renewal and gentrification (U.S.) • Dialogues for sustainability • Rise of "Cities as solutions" • Aging infrastructure systems	• Conservation and integrated management • Point- and non-point-source pollution controls • Separate regulations for combined and separated sewers • Pipe leakage and maintenance • Increasing costs for treatment • Increased interest in ecosystem services • Concerns over scarcity (water and energy) and climate variability

4.1 Walking cities: Establishing patterns (1800-1860)

Cities first developed foundational infrastructure and layouts when walking was the predominant mode of transportation, and growth was the preeminent goal. Infrastructure growth was driven by economic development (Warner 1978; Schott 2004), public health concerns (Blake 1956; Moehring 1981), safety (Blake 1956), and political responses to vocal interest groups (Gluck 1979). For centuries, the layout of cities in

Europe, Asia, and the Americas facilitated walking. In a few cases, however, water facilitated travel and commerce. Venice, for example, used waterways to move people and goods quickly in a crowded urban area. From the Middle Ages onward, the city's leaders appreciated the value of lagoons and worked to maintain drainage and harbors on the island. In 17^{th}-century Amsterdam, canals were used to support the thriving Dutch capital (Radkau 2008). These examples of extensive internal water transit were the exception, since water transportation was primarily for external commerce.

In the newly established cities of the U.S., walking dominated transportation until the mid-1880's. Cities often located in areas of compact terrain with access to raw materials and inexpensive transit, primarily near water. Through this period, municipal responsibilities expanded from regulation of commerce and modest works projects such as unpaved streets to broader professionalization of services including fire, police, and construction. Cities also expanded municipal oversight of infrastructure development, first through council committees and later departments. This led to the professionalization of utility services. Even still, many efforts were piecemeal and focused on a block or street. Most financing for public works projects came from state and local sources, with the federal government financing a few sectors such as river and harbor improvements or railroads (Aldrich 1980). States were particularly involved in large projects such as canals, with many agreements forged as public-private partnerships where the government was an investment catalyst (Lively 1955; Blake 1956). Municipal debt increased rapidly and investments were subject to volatile economic cycles. In established cities such as New York, Cincinnati, and Boston, governments took responsibility for water delivery by consolidating public ownership of many local water sources and funding new projects (Blake 1956). The latter half of the period (1840's) also saw cities investing in railroad infrastructure in a competitive race for economic development (Tarr 1984). This subsided by the 1850's, however, and even as mechanized transport grew, street life dominated urban patterns and walking remained the primary mode of transit.

4.2 Industrial growth and core infrastructure (1860-1910)

Industrial growth, mechanization, and the settlement of western North America defined a new era of urban growth that created the "core infrastructure" of central cities between 1855 and 1910 (Tarr 1984). The era can be further subdivided into two parts. During early decades (1850-1890), many cities began to establish core water supply and distribution systems, resolve competing sewer designs, and construct large bridges. During later decades (1890-1910), a more "sustained thrust" (Tarr 1984) across the nation, developed through both public and private means, significantly increased access to centrally-supplied water and sewer services, as well as transportation systems with bridges, highways, and paved roads. Municipal governments deployed a host of new technologies for transportation (steam and electric-powered streetcars), energy (incandescent bulbs, centralized electricity production, distribution systems and transformers), water distribution (pumps and waterworks, filtration and chlorine treatment, reservoir and storage facilities), wastewater (central sewer systems), and communications (telephone and telegraph) (Warner 1978; Tarr 1984). Networks of infrastructure grew (Tarr 1984; Hughes 1993) and cities sought to clean and beautify neighborhoods, exemplified by the City Beautiful movement (Hall 1988; Duffy 1990). Cities expanded as wealthier residents moved to new peripheral neighborhoods opened up by the construction of streetcar, trolley, and regional rail systems. The profession of consulting engineers expanded rapidly. In sanitary and water engineering, for example, well-known founders of the field such as Allen Hazen, George Whipple, and George Waring were widely employed by many cities (Armstrong et al. 1976). Key organizations such as the American Water Works Association, which was established in 1881, spread expertise and knowledge of urban water distribution and treatment technologies. Urban development was also uneven within cities, where wealthier residents often had much greater access to services, as well as across cities in different geographic areas, with the Northern and Midwestern cities building much faster than those in the South.

4.3 The rise of North America and its cities (1910-1950)

The rapid growth of the Ford automobile company, founded in 1903, symbolized a coming era (1910-1950) in American urbanization: the rise of personal transit through the automobile (Tarr 1984). The increasing affordability of automobiles gave urban residents freedom of mobility and encouraged sprawl. It also forced cities to develop roads and highways for transportation into and out of cities. The structure of roads in cities changed to multi-lane, single-direction streets (Tarr 1978). The result was a rise in suburban and ring communities, especially after World War II. Cities used taxation and debt-financing from local, state, and national sources to build bridges, pave streets, and later create secondary arteries to bring residents in and out of central business districts (Aldrich 1980). In the later part of the era, growth became increasingly uneven, with urban development "leapfrogging" areas of rural land as new areas were shaped by property rights, geography, and politics (Whyte 1958).

The first half of this era saw a large transition in political views of efficient management. While many cities were still run by political machines, reformers called for new forms of government that could improve efficiency and reduce the patronage system that dominated public works and sanitation. As early as 1887, Woodrow Wilson advocated for a professional civil service, trained in bureaucracy and more insulated against corruption. With his election to the presidency in 1913, the expertly-trained civil servant became engrained. Cities professionalized service delivery and adopted new forms of organization and administration (Tarr 1984).

During the Great Depression of the 1930's, federal governmental involvement in infrastructure development expanded rapidly in water, transportation, and electricity through public employment programs. The Public Works Administration (PWA) and the Works Progress Administration (WPA) were both key funders of municipal sewer construction. The population served by municipal sewers increased from 21.5 million in 1932 to 39 million in 1939 (Tarr 1978). This Progressive Era of investment was followed by a massive increase in national spending for the Second World War. While Europe and Japan were decimated, the U.S. vaulted to global leadership through its industrial might, vast capital resources, and technological prowess.

This leadership position quickly led to new infrastructure developments that would shape the nation for decades. By the 1950's, the federal government, buoyed by national security concerns and a large collection of vocal constituencies, funded and developed a national system of interstate highways for rapid automobile and truck transit through the Interstate Highway Act. To date, the interstate highway program and its funding mechanisms are one of the strongest examples of the expansion of federal involvement in infrastructure. During this era, too, early water quality legislation increased research and facility construction for urban water treatment.

4.4 Radial expansion, central planning, and environmentalism (1950-1987)

With individualized automobile transportation infrastructure in place, cities grew outward. For several decades (1956-1990), middle- and upper-class families flooded to expanding outer ring suburbs, driven by the opportunity to have more land within easy commuting distance of central business districts. Additionally, many formerly urban-dwelling, affluent, middle-class families fled inner-city residences out of fear of racial tensions. Inner city neighborhoods degraded as tax bases collapsed and crime rose. Planning and management agencies responded in many cases with urban renewal projects that demolished existing neighborhoods to build government-sponsored low-income housing. Such designs were inspired by architecture and urban planning trends of the Garden City Movement, which sought to separate urban buildings through upward expansion and surrounding green spaces that let the city "breathe." Additionally, transportation planners constructed highways through urban centers, especially in traditionally minority-dominated neighborhoods (Hall 1988). In New York City, for example, administrative planner Robert Moses used uniquely powerful political influence to undertake massive highway construction projects that connected dense urban cores with peripheral areas in Long Island and upstate (Caro 1974). These approaches emphasized centralized management and design of infrastructure. Through programs and funding, the federal government claimed an increasingly important role in financing transit. Yet, many projects targeted low-income and minority neighborhoods. The automobile facilitated such changes, but planning processes drove sprawl and redevelopment (Jacobs 1961).

Through the 1960's and beyond, two trends dominated urban infrastructure. First, the U.S. environmental movement gained momentum, rooted in growing concerns over pollution from urban, industrial, and agricultural sources. The seminal Clean Water Act of 1972 laid the foundation for several decades of legislation, which sought to prohibit point- and non-point- sources of water pollution. Cities and industrial "dischargers" of wastes were now required to obtain permits and provide evidence of compliance with federal regulations. Second, as many formerly vibrant central cities degraded, outer ring suburbs expanded and strained highway and transit systems. Shrinking urban cores were left with oversized, aging infrastructure and declining tax revenues. Road and highway construction continued, but commutes and congestion in major urban areas grew (Tarr 1984). At the same time, local movements began opposing plans to expand urban highway and transit infrastructure at the expense of core, inner-city neighborhoods. The battles between urban sociologist Jane Jacobs and Robert Moses in the early 1960's embodied the vocal objections of urban citizens to highway-focused planning in cities throughout the country. Jacobs (1961) also captured a nascent trend that emphasized street life, critiqued central planning, and foresaw the relevance of emergence and self-organization in complex social networks. Her work is a theoretical and practical foundation for subsequent eras of urban planning that emphasize mixed-use design and multi-scalar development.

4.4.1 The doctrine of central planning

Nevertheless, the more decentralized era of planning envisioned by Jacobs was yet to come. Operations research and modeling techniques developed in the 1960's informed systems approaches to solving urban problems. Urban planning by central authorities was intimately linked with expert-driven, rational planning. For instance, writing in the 1970 publication Treatise on Urban Water Systems, Paulsen described the concern of increasing fragmentation of urban and regional bureaucratic structures. Management authorities were created haphazardly to respond to the problems of water supply, garbage collection, public health, congestion, zoning, and more. Paulsen argued that the remedy was a systems approach that bridged local, state, and national agencies to ensure that "plans are laid from the very beginning with the intent to implement" (emphasis original) (p. 15). The phases of problem solving included:

- Formulation of concepts
- Design of proposed systems
- Development of equipment and procedures
- Demonstration of prototypes
- Engineering evaluation and acceptance
- Construction and installation
- Sustaining of operational capabilities.

Paulsen noted that, "[i]f the program envisions these phases as successive steps from the very beginning, the deadly sin of planners will have been avoided. The sin is this: to plan with no provision for closure, no intent to implement" (p. 16). While work in water and transportation recognized the opportunity for systems analysis and modeling approaches to solve connected urban challenges, public involvement is not specifically noted, instead emphasizing the role of the expert planner in charting the future city. Notably, similar critiques of dispersed urban management duties across agencies appear today in urban water (Hering et al. 2013; Kiparsky et al. 2013).

4.5 Revitalized neighborhoods and sustainability goals (1987-present)

During the 1980's, city administrators in the U.S. faced shrinking budgets eroded by a loss in population, while federal government deficits increased sharply from military spending and tax policies. As budgets shrank, costs for operating and maintaining the nation's aging municipal and transit infrastructure rose. Additionally, governments now had to address increasingly apparent externalities of air and water pollution created by sewage and stormwater disposal, rapid automobile growth, fossil fuel combustion, and industrial processes. Retrofit and remediation efforts were costly. New environmental movements appeared, embodied by the seminal report of the U.N. World Commission on Environment and Development (Brundtland Commission) in 1987 entitled *Our Common Future*. It outlined a vision and definition for growth, which was to be central for sustainability initiatives in later decades.

Even as many cities outside of the U.S. prospered through the 1980's and 1990's, U.S. urban regions were still dominated by central business districts with daytime activities and suburban and satellite neighborhoods where middle- and high-income residents lived. Slowly, however, historic neighborhoods in San Francisco, Washington, D.C., Boston, and New York began to grow again, fueled by younger professionals with different lifestyle attitudes. Block-by-block, public and private entities refurbished existing building stock, replaced old water, sewer, and electricity lines, and expanded cellular and wireless telecommunications networks. Throughout North America, the migration of young professionals and "empty-nesters" (older adults whose children have moved out) to denser urban neighborhoods drove a fundamental shift in urban land development. Cities emphasized revitalization goals that shifted from auto-centric transportation and planning toward renewed street life, mixed-use neighborhoods, and community development. Many new urban residents that rapidly gentrified U.S. cities through the early 2000's were more likely to abandon automobiles as a primary mode of transit. The lifestyles and amenities sought by new urban residents also coordinated with goals of urban planners to support more "sustainable" forms of urban development, while promoting an expanding commercial tax base. Yet, cities still face high costs to maintain or redevelop existing infrastructure and address persistent problems of air, water, and soil contamination. In past eras, the federal government provided significant funding to communities for building such infrastructure. Today, cities bear more of these costs. They are receptive to new approaches to address long-term energy and environmental problems in a cost-effective manner.

4.5.1 Ecology, design, and sustainability in cities

While urban sustainability has rapidly penetrated public discussions in the past decade, a long history of urban research explores the interaction of cities with their environments (Howard 1902; Geddes 1914; Mumford 1961; McHarg 1969; Alexander 1979; Hall 1988; Cronon 1992; Calthorpe 1993; Wheeler 1998). Definitions of sustainability typically relate social, environmental, and economic tradeoffs for current and future generations (Brundtland Commission 1987; Common 1995; Wheeler 2004). Putting this concept into practice has proved challenging (Solow 1993; Arrow et al. 1996; Dasgupta 2007).

The science of urban ecology is enlightening our understanding of ecosystem processes in cities (Pickett et al. 2001, 2011; Alberti 2008). Renewed interest in urban development, brought on by significant growth in urban populations worldwide, is driving new goals and approaches for urban systems. Urban management of the late nineteenth- and twentieth-century sought to provide residents of industrializing cities with centralized services to ensure clean and healthy environments through highly-managed interventions and regulated ecologic functions (Melosi 2000). The new era of sustainable cities considers energy use, urban ecological processes, landscape design, and green infrastructure to develop urban forms that promote conservation, reuse, and environmental quality (Pincetl 2007; Novotny et al. 2010). While these laudable goals are being taken up by many cities, urban residents of industrializing cities, as well as residents in some neighborhoods of affluent cities, still struggle to achieve safety and health. New urban designs that emphasize greening and technology may maintain or even exacerbate inequality.

5 Development Eras in Urban Water Infrastructure

Water infrastructure is an important and ancient component of urban life. Since the earliest urban settlements, cities have built infrastructure to manage rainfall, control flooding, and supply water. Early civilizations constructed water management systems for supply and irrigation. Societies in Iran and Greece exploited local and regional water sources through managed projects to supply water for residents. The Romans, the most expansive of ancient Western societies, engineered aqueducts, fountains, *castellan* (storage facilities), cisterns, and pipes on a large scale to supply fresh water to and remove sewage from cities throughout the empire, including Pompeii, Rome, and Carthage (Wilson 1998). Sophisticated Roman designs even incorporated quantitative analysis (Frontinus 97AD; Wolfe 1999). Beyond Rome, civilizations throughout the world built infrastructure to manage and control water. Novotny et al (2010) make a distinction in these early cities (B.C. to middle ages). Many provided basic water supplies for drinking and bathing through local wells and rivers, with streets and culverts used to convey rainfall runoff and wastes. But some societies such as Greece and Rome, as well as European cities in the Middle Ages, built more complex engineered systems that covered long distances. Water imports supplied public fountains, baths, and some affluent households, using an energy gradient between the distant elevated aqueducts and city centers. Sewers and street culverts removed stormwater and wastes from limited flushing toilets, though most residents used cesspools and cisterns to capture wastes.

In modern urban water systems, infrastructure supplies and conveys water through several systems. First, water distribution systems take water from multiple sources, including groundwater, surface water, and recycling, and distribute it to meet a range of urban water demands. Second, used water (wastewater) conveyance and treatment systems remove sewage from buildings and treat it for reuse or later disposal in local surface water and groundwater. Third, rainwater and stormwater systems manage runoff from rainfall, irrigation, and other sources through sewers. Some systems carry only stormwater (separated sewers) and others combine wastewater and stormwater collection (combined sewers). Fourth, distribution systems supply water for fire fighting, which requires sufficient pressure and availability. Earlier decentralized and labor-intensive systems, where individual households were responsible for ensuring healthy supplies, evolved to centralized and capital-intensive systems where cities communally ensure quality and reliability. With municipal control, water, wastewater, and stormwater systems were managed in separate departments, or sometimes even in separate agencies, in a municipal region. Over two centuries of industrialization, cities designed infrastructure to first manage water supply, then sewage, drainage and environmental quality in waterways and local water bodies (Brown et al. 2008).

Publicly-managed urban water systems were not always common. As North America cities grew in the 1800's, they often granted water supply concessions to private companies that served only some neighborhoods. In time, cities recognized the need for larger, comprehensive systems to fight fires and prevent disease (Blake 1956). Municipal governments took over many private water supply companies. Publicly-owned water providers could leverage cheaper capital resources and ensure better reliability. They also assumed water supply functions as part of a larger strategy to promote growth and publicity. Yet, private municipal suppliers still exist. In much of California's Silicon Valley, for example, private firms still dominate water supply. Since the 19th century, the mix of public and private control for urban water delivery can best be described as a shifting landscape of trends, but not absolutes (Swyngedouw et al. 2002).

5.1 From private to public: Early water systems in the U.S. (1800-1880)

In the late eighteenth century, U.S. cities realized the need for water sources more reliable than local springs and rivers. Many cities were located along coastal areas with local sources of poor quality. Springs or rivers provided the best water in these environments. Once hyper-local sources were depleted or contaminated, cities obtained water from peripheral sources using a network of carriers, whose deliveries were often of poor-quality and brought over distances of several miles. Early in U.S. cities, most urban water systems were built by small, private companies who were granted charters to raise capital and deliver water from local sources. The companies served limited, often wealthier, neighborhoods (Swyngedouw et al. 2002). Philadelphia was an early exception. In 1801, it hired Benjamin Latrobe to build the city's first municipal water supply at the Center Square Water Works. Latrobe designed a system of reservoirs, steam-powered pumps, canals, and wooden pipes to divert Schuylkill River water into the central city. This design won out over plans by a private company to build a dual-use canal between Lake Erie, Lake Ohio, and Philadelphia.

The facility, however, was not a financial success and was replaced in 1812 with a more efficient one, the Fairmont Water Works (Blake 1956).

For cities with privatized suppliers, early corporate proprietors often had strong connections with the municipal officials making decisions regarding public financing of water. In a few instances, the proprietors were themselves the decision-makers. For example, in New York City, state assemblyman Aaron Burr developed a bill to charter a Manhattan Company that would provide water to the city. The charter was defeated by New York voters. In the state assembly, however, Burr altered the bill to charter the Manhattan Company with banking privileges; it later turned into Chase Manhattan Bank and J.P. Morgan Chase. To appease public opinion, however, the company directors voted to continue the mission of providing water. It took several decades for angry New York residents to demand that the city build a large-scale canal from the Croton River to replace the tepid, distasteful, and contaminated water from the Manhattan Company (Blake 1956).

Many cities also had competing suppliers. In Houston, for instance, public waterworks projects began in 1859 with construction of a few public cisterns (Green 1915). Spurred by the need for fire protection and clean water, however, the city council contracted in 1879 with a private group of individuals, the Loweree group, for the city's water needs. Renamed the Houston Waterworks Company, it drilled its first artesian well in 1888 (Melosi 2001).

Over time, residents and leaders in early U.S. cities realized the limitations of private water delivery. Initial water works companies successfully raised ample funds from enthusiastic investors, but supplying a whole city required more capital (Blake 1956). City councils were driven by the "twin scourges of fire and disease" to seek more reliable options. Yellow fever, cholera, and typhoid epidemics were all common in quickly urbanizing cities of North America. These cities had a "substantial mortality 'penalty'" through the nineteenth century, with urban mortality rates 30% higher than in rural areas (Haines 2001). Cutler and Miller (2005) estimate that in 1900, 44% of deaths in major cities were due to infectious diseases. A worldwide cholera outbreak in 1832 created panic among city leaders in Europe and North America. Public health experts believed that diseases were spread through foul-smelling air and it took several more decades for epidemiologic studies in London to identify the causes of cholera. Nevertheless, experts and leaders believed that improved water supplies could help to clean the air of disease.

This era of increasing public health concerns, led by the *sanitarians,* coincided with other justifications for better water supplies. In New York City, for example, public distaste of the foul Manhattan Company water combined with fire and disease prevention goals to forge a consensus on funding water infrastructure improvements (Blake 1956). Many cities, including New York, Baltimore, and Boston, as well as many smaller cities, transitioned from private to public systems under the threat of disease and promise of economic growth. Cities founded later in the expanding west showed similar patterns. In Houston, as the city sought to expand services and reliability, in 1906, it purchased the private Waterworks Company and made it a municipal entity. This purchase occurred in an era where, "municipal leaders increasingly argued that cities could run their services more efficiently and effectively than private firms who were driven simply by profits" (Melosi 2001). Over time, cities municipalized water delivery and sewage conveyance to create a more "sanitary" city (Tarr et al. 1984; Duffy 1990; Swyngedouw et al. 2002).

5.2 Treating water supplies (1880-1920)

In the late nineteenth century, migration fueled rapid growth in industrial cities in the U.S., especially in the Northeast, Midwest, and West. Cities sought to support this growth, which also benefited political leaders, by funding reliable water supplies from local and regional sources. Capital-intensive solutions to water scarcity tapped distant (surface water) and deeper (groundwater) sources to replace nearby polluted ones. New York City was an early leader, beginning construction on the Croton Dam and Aqueduct in 1837 after lengthy debate. Its first aqueduct was completed in 1842, but a larger new aqueduct was only finished in 1890. In the

West, the first extension of the Los Angeles Aqueduct was completed in 1913 (Reisner 1993). These large-scale facilities were expensive and limited to bigger cities in need of clean water supplies from relatively pristine watersheds, often in higher elevations. Yet, even with new capital-intensive infrastructure for fresh water, epidemics still raged in cities, driven by systems that allowed sewage to drain into municipal supplies. Many cities had primary sewer outfalls upstream of water intakes (Duffy 1990).

While cities built importation infrastructure and faced continued health concerns, new technologies became available. Filtration technologies, including the slow-sand filter in England and the rapid-sand filter in America, grew more popular and offered options to purify local and imported water (Baker 1948). Scientific research into microbiology and bacteriology increased significantly during this period, and experiments with filtration technologies began to reduce disease outbreaks, especially typhoid fever. In 1881, the American Water Works Association was established to spread knowledge and expertise of urban water systems construction. Further, from 1900-1910, chemical treatment advances, especially chlorination, offered cities a cost-effective way to augment filtration with more effective treatment (Cutler & Miller 2005). By the end of World War II, larger cities throughout the U.S. were combining pristine water from distant sources with filtered and treated local supplies (Melosi 2000). Newly available supplies often created large increases in per capita consumption, fueling a cycle of continued shortages. Table 3 below shows the dates that many U.S. cities brought filtration, chlorination, and treatment systems on line for water distribution and sewage.

Table 3: Year of implementation for water treatment technologies, by city (Source: Cutler & Miller 2005)

City	Water Filtration	Water Chlorination	Sewage Treatment	Sewage Chlorination
Baltimore, MD	1914	1911	1911	after 1936
Chicago, IL	after 1940	1916	1949	after 1949
Cincinnati, OH	1907	1918	after 1945	after 1945
Cleveland, OH	1917	1911	1922	1922
Detroit, MI	1923	1913	1940	1940
Louisville, KY	1910	1915	1958	after 1958
Milwaukee, WI	1939	1915	1925	1971
New Orleans, LA	1909	1915	after 1945	after 1945
Philadelphia, PA	1908	1913	after 1945	after 1945
Pittsburgh, PA	1908	1911	after 1945	after 1945
St. Louis, MO	1915	1919	after 1945	after 1945

5.3 The sewage problem (1880-1920)

As cities developed water distribution infrastructure to meet growing demands, increased per capita water use created a new problem: large amounts of wastewater (Tarr et al. 1980; Melosi 2000). Traditionally, many buildings used local cesspools to store and break down sewage through crude anaerobic processes. With the advent of the toilet, wastewater soon overwhelmed household management capabilities. Cesspools leaked, causing soil and groundwater contamination. Sewers, meanwhile, were primarily intended for stormwater drainage, both public and private (Tarr 1984). The rapid expansion of American cities, combined with space constraints, created a problem of surplus for sewage and wastes (Tarr et al. 1980). Cities had to develop innovations in both decentralized and centralized wastewater treatment technologies even with limited scientific understanding of metabolic and bacteriological processes. Contentious debates ensued over municipal spending and infrastructure expansion (Blake 1956), but eventually, public health concerns motivated municipalities to adopt centralized, sub-surface sewage conveyance.

This development, however, was founded on a false premise, "Miasma" theory, which believed that diseases were transmitted by smelly and dirty air. As early as 1845, sanitarians advocated for the link between health, cleanliness, and disease transmission. In his 1842 seminal report entitled *The Sanitary Condition of the Labouring Population of Great Britain,* Sir Edwin Chadwick argued for an arterial system with pressurized water delivery and removal to improve urban health. The approach quickly spread to New York and other cities in North America, motivated by continued outbreaks of cholera and typhoid (Melosi 2011). The spread of knowledge spurred new local plumbing codes and regulations, including local health boards to oversee epidemic responses (Tarr et al. 1984). Sanitarians also advocated changes in regulations and municipal oversight (Duffy 1990). From 1870 to 1920, the percentage of the urban population with access to sewer services rose from 4.5% to 47.5% (Pearse 1938). In contrast, the percentage of rural populations with municipally-treated sewage rose from less than 1% in 1870 to 18% in 1920. Table 4 lists expenditures on sewer construction and water filtration between 1881 and 1910.

Table 4: Municipal Expenditures on Sewers and Water Filtration Systems (in 1929 Dollars), 1881-1910 (Source: Aldrich 1980)

	Spending (in millions)		Percent
Period	*Sewer Construction (1929 Dollars)*	*Water Filters (1929 Dollars)*	*Real Sewer and Water as percent of State and Local Construction*
1881-85	13.12	0.08	7.60%
1886-90	17.8	0.11	8.30%
1891-95	9.3	0.47	3.60%
1896-1900	11.3	0.6	3.50%
1901	14.2	1.65	3.10%
1906-1910	17.4	4.16	2.80%

5.3.1 Combined and separate sewers

Urban drainage systems remove both sewage and runoff. While residential, commercial, and industrial wastewater outflows (sewage) are predictable, runoff from precipitation is variable. Two types of system designs were typically developed for drainage: combined sewer systems (CSSs) and separate sewer systems (SSSs). In combined sewers, wastewater and runoff move through the same network of pipes. In separate systems, however, storm sewers for runoff are not connected to sanitary sewers for wastewater. Through the nineteenth century, most large cities built combined sewers since they lowered construction costs by removing duplicate networks of pipes. By 1909, 74% of U.S. cities with municipal sewer systems had combined sewers (Tarr et al. 1984). Yet, combined sewers also made it more difficult to recover nutrients from wastewater flows and cities predominantly dumped the raw sewage in local water bodies. This reinforced the growing problem of water treatment:

> The irony was clear: cities had adopted water-carriage technology because they expected local health benefits resulting from more rapid and complete collection and removal of wastes, but disposal practices produced serious externalities for downstream or neighboring users… This, then, was the primary unanticipated impact of sewerage technology- a rise in health costs where health benefits had been predicted (Tarr et al. 1984 p. 239).

Some smaller cities of the period adopted separate systems, but most cities of the Northeast, Midwest, and Mid-Atlantic built out combined systems that are often still in use today (Melosi 2000; EPA 2004).

5.4 Regionalization, pollution, and environmentalism (1920-1982)

Following the era of Progressive Reform, U.S. municipal and industry leaders continued advocating for expanded municipal water and wastewater systems. While the large metropolitan areas such as New York, Boston, Philadelphia, Cleveland, and other industrial centers built water treatment technologies through 1920, many mid-sized and smaller cities could not afford these expensive systems. Sanitarians such as Abel Wolman and Linn Enslow, who together in 1926 developed improved chlorination processes for use by a greater diversity of municipal systems, expanded the reach of cost-effective technologies (White & Okun 1992). Such Many sanitarians worked in both scientific research and practical applications.

As municipalities implemented distribution and treatment systems for water, wastewater, and stormwater, the nation as a whole was experiencing changes in its role in the world. In response to the Great Depression of the 1930's, President Roosevelt devised a series of publicly-funded infrastructure development programs to invigorate the economy as part of the New Deal. The Public Works Administration (PWA), Works Progress Administration (WPA), and the Tennessee Valley Authority (TVA) were just a few of the many conduits that moved federal money into public works. Many projects focused on large dam construction, rural electrification, and transportation. In addition, through the New Deal, the federal government took a major role in developing urban infrastructure, including roads, sewers, waterworks, dams, bridges, parks, docks, airports, and public buildings (Aldrich 1980). Furthermore, the federal government took on a role in dictating sewer system design. Tarr (1984) notes that:

> [Public Works Administration] funds accounted for 35 to 50 percent of all new sewer and water supply construction during the 1930s. These projects generated a variety of benefits to local communities. New water supply systems, for instance, produced sharply reduced fire insurance premiums in addition to water supplies. Sewer construction supplied unemployment relief and also addressed the problems of water pollution control. President Roosevelt accelerated investment for sewage treatment facilities by refusing to approve PWA sewer projects that did not include treatment. Similarly, the Works Progress Administration (WPA) was not permitted to construct sanitary sewers unless they were designed to be compatible with treatment works. By 1938, federal financing had aided in the construction of 1,165 of the 1,310 new municipal sewage treatment plants built in the decade. The population served by sewage treatment increased from 21.5 million in 1932 to more than 39 million by 1939, substantially improving the quality of the waterways used for municipal waste disposal (p. 41).

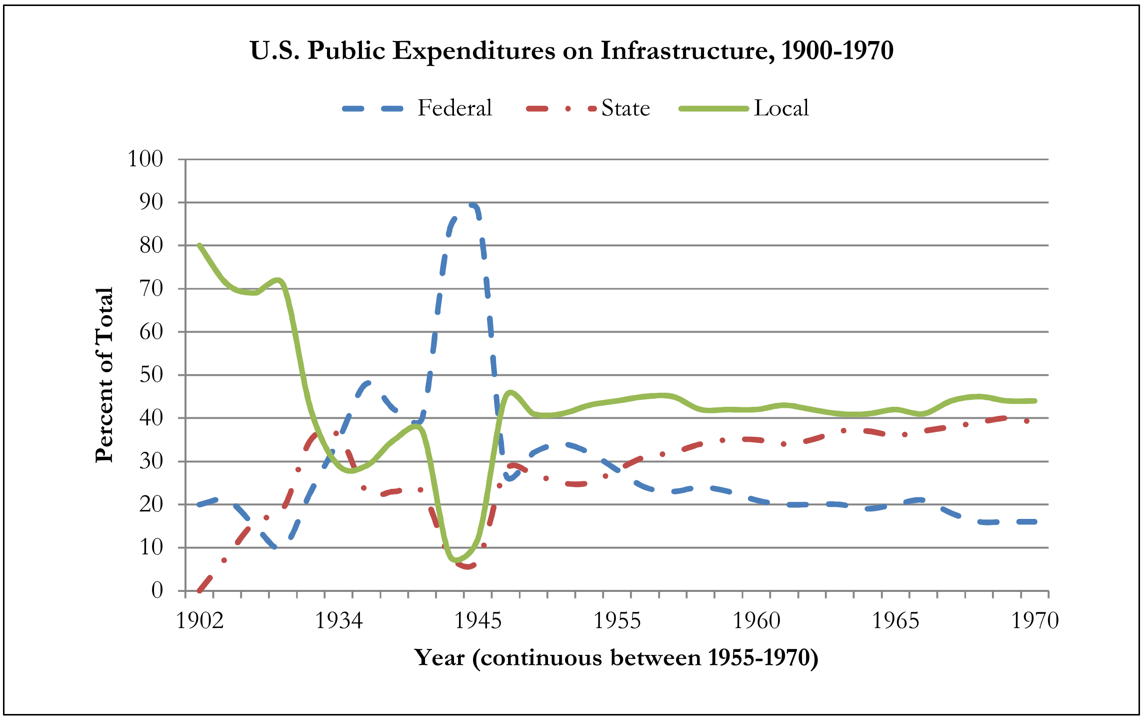
The PWA financed 2,400 to 2,600 water projects at a cost of nearly $312 million (nominal), which was "half of the total expenditures for waterworks for all levels of government" (Melosi 2011). Other agencies, including the Civil Works Administration and the WPA, spent an additional $112 million on labor related to municipal water. The funding infusion had the greatest impact on localities (Scientific American 1944; Melosi 2011). Figure 1 shows total U.S. public expenditures on infrastructure between 1900 and 1970 from federal, state, and local sources.

Following World War II, total public investment in infrastructure resumed, increasing from $8.6 billion to $13.6 billion between 1950 and 1960 (Aldrich 1980). Pre-treatment clarification and filtration became more widespread in municipal services, while chlorination, aeration, and water softening techniques also grew. With more spending came centralized bureaucratic control. Operations and management of water, wastewater, and stormwater systems was dispersed across departments or even across agencies. Bureaucratic fragmentation emerged from technocratic, specialized approaches to systems management.

Spending during this period was in part motivated by growing recognition of old, ineffective infrastructure in many cities (Melosi 2011). From 1945-1965, municipal water works in the U.S. increased from approximately 15,400 systems serving 94 million residents to over 20,000 systems providing for 160 million people (Babbitt & Doland 1955; Fair & Geyer 1958). As federal infrastructure spending increased, federal legislation also began to address urban water pollution. In 1948, the U.S. Congress passed the Water Pollution Control Act, which established baselines for water quality to protect human health. Subsequently, the Federal Water

Pollution Control Act Amendments of 1961 and the Water Quality Act of 1965 followed, which provided funding for infrastructure improvements and required states to develop water quality standards. Still unsatisfied with state progress, Congress passed a "comprehensive recodification and revision of federal water pollution control law, known as the Federal Water Pollution Control Act (FWPCA) Amendments of 1972. The FWPCA regulated discharges from point-source pollution sources through the National Pollutant Discharge Elimination System (NPDES), focusing on industrial sources and municipal sewage. In totality, the legislation created a blanket of regulations that forced cities to develop advanced wastewater treatment facilities to control effluent. The growth of legislation corresponded with a national and international public awakening on the consequences of environmental degradation and industrial pollution.

Figure 1: U.S. public sector expenditures between 1900-1970, broken down by level of government. Data is continuous between 1955-1970, but represents only a subset of years between 1900-1955. Data adapted from Tarr et al 1984, based on data from the 1975 U.S. Historical Census (Census 1975)



5.4.1 Economics and geography of regionalization

Many cities, especially large ones, faced the critical problem of supplying water to a concentrated population of residents with ever-increasing demands. To meet such challenges, cities expanded their controlled water systems in several ways. Most secured fresh water from increasingly distant watersheds and underground aquifers by building centralized facilitates such as pipelines and treatment plants. Acquisition costs for new water sources are driven by the location, quality, and elevation (or depth) of sources, while distribution costs result from the distance between users and central distribution nodes (treatment plants), as well as pumping costs (Coase 1947; Clark & Stevie 1981; Lund 1990). Many large city utilities also absorbed smaller regional systems to get more access to water sources and improve economies of scale. In some cases, though, surrounding communities maintained separate jurisdictional status as incorporated cities or larger counties. Over time, regional water systems arose in many metropolitan areas through agreements between distinct but cooperating jurisdictions. Regional systems expanded as larger jurisdictions transferred excess supplies from cheaper centralized sources to regional communities (Capen 1975; Lund 1988). Bureaucracies grew to control the water resources and new technologies.

5.5 Scarcity and conservation (1982-present)

Suburban growth through the 1980's forced cities to invest heavily in distribution systems for peripheral, lower-density areas. Distribution costs often made up two-thirds of overall system operating expenses (Larson 1966; Clark & Stevie 1981). Additionally, water shortages became more frequent with urban growth. In western regions of the U.S., many arid cities faced expanding populations and a shrinking base of unexploited water resources. In California, for instance, the large-scale Central Valley Project (federal) and State Water Project (state) conveyance systems provided new sources of water for growing Southern California cities, but also signified the end of readily available water (Reisner 1993). While some new sources were still available, opposition to large water projects grew. In 1982, Proposition 9, also known as the Peripheral Canal Act, sought to build a large canal on the periphery of the Sacramento-San Joaquin Delta, which would move water from Northern to Southern California. The measure, however, was rejected under strident geographic and political divisions. In a state that had continually funded new conveyance measures to address water demands, the defeat of the peripheral canal signaled a new era. Subsequently, southern California cities, and later cities throughout the state, emphasized conservation and water recycling for managing water. They relied heavily on timely conservation to manage water scarcity during droughts. Since 1995, urban water use has not grown significantly for California cities (Hanak et al. 2011).

The new approach to urban water management, which included conservation, "fit-for-purpose" water supplies (i.e. aligning sources of different water quality with appropriate uses), technology, and integration, embodied an era of "water cycle cities" (Brown et al. 2008). Southern California cities explored innovations such as direct potable reuse, groundwater recharge, and desalination. In Los Angeles, aquifer recharge using stormwater began in 1938 when it opened the "spreading grounds" at Rio Hondo and San Gabriel. These facilities capture controlled and uncontrolled upstream releases from streams and percolate it to groundwater in large shallow ponds. The Rio Hondo facility covers 430 acres with 20 shallow ponds that can percolate an average of 400 cubic feet per second (cfs), while the San Gabriel facility covers 96 wetted acres in a basin and 308 acres in an unlined river channel; the two components can percolate a combined 150 cfs. Imported and recycled water were introduced in 1953 and 1962, which, when combined with stormwater infiltration, provide sufficient recharge to make up for overdraft in the Central Basin (Johnson & Gagan 2011). Today, the region is examining ways to augment infiltration to achieve multiple goals, such as improving the quality of surface water runoff and increasing sub-surface recharge (LADWP 2010).

Trends in California mirror water conservation efforts in other arid cities. Per capita consumption in North American cities, however, is still significantly higher than many other industrialized countries in Europe, Asia, and Oceania (Gleick 2003; Cahill & Lund 2013). Water conservation is often the most economical strategy to manage urban water scarcity, but entrenched social and personal habits take years or even decades to change. At the same time, groundwater resources are becoming contaminated and depleted in many parts of the West. In surface water, as well, agricultural and urban runoff can decrease water quality, produce high levels of suspended solids, and harm sensitive aquatic species.

5.5.1 Regulating combined sewers

This period also saw growing recognition of the problem of Combined Sewer Overflows (CSOs). As described earlier, many large U.S. cities in the Northeast and Midwest, as well as scattered newer cities in the West, built combined sewers for both sewage and runoff. This lowered overall construction costs, but it also created great variability in the volume of flows. During large rainstorms and floods, combined sewer pipes, which were not necessarily sized to meet the largest predicted storms, could overflow in some areas as the volume of urban runoff overwhelmed capacity. This would spill raw sewage through outfalls to local water bodies. As federal and state regulations implemented treatment requirements for wastewater discharges, cities with these CSSs faced high costs to retrofit systems and prevent CSOs.

Through the National Pollutant Discharge Elimination System (NPDES), dischargers of industrial and municipal sewage are required to obtain permits. The CWA regulations, which focused on technologicallyachievable implementations to improve water quality, regulated specific contaminants using measures of 5-day biochemical oxygen demand, total suspended solids (TSS), pH, fecal coliform bacteria, and oil and grease (U.S. EPA 2012). The Water Quality Act of 1987 broadened the CWA regulations to include industrial and municipal stormwater discharges, as well as smaller municipal separate storm sewer systems (MS4s), through a phased implementation program (U.S. Code 1987). For municipalities, Phase I regulations (1991) encompassed systems serving 100,000 people or more, and Phase II (2003) that required all municipalities comply with non-point source pollution requirements. In 1994, the EPA required municipalities to improve CSO-related pollution problems, and Congress amended the CWA in 2000 to mandate municipal compliance with the policy through the Combined System Overflow Control Policy (U.S. EPA 2000).

5.6 A new "paradigm" of urban water management

With the global growth of cities and increasing emphasis on environmentally-friendly urban development, Novotny et al (2010) call for a new paradigm of urban water resources. The new era emphasizes integrated water management and equal goals for environmental quality, economic prosperity, and social development (Daigger 2011). This paradigm of water infrastructure incorporates water reuse, landscape-based contaminant removal through infiltration and green infrastructure, and conservation to meet the potentially competing goals of "sustainable" urban development. Institutional reform that integrates disparate functions and includes citizen involvement is also an important component of sustainable water management (Brown 2005; Brown & Farrelly 2009). Better understanding of ecological processes and improved coordination between engineers, urban planners, architects, and city administrators can improve stormwater system design. Codifying standards into city codes for new construction can also minimize regulatory costs. Local retention, storage, and water reuse for irrigation and drinking may reduce long-term infrastructure and pumping costs (Mihelcic et al. 2003). While traditional utility planning emphasized imported supplies and wastewater conveyance, the new era seeks to reduce per capita consumption by emphasizing more localized supply and reuse, environmental design, and citizen participation to create more "water-sensitive cities" (Wong & Eadie 2000; Brown et al. 2008).

Even with this recent scholarship, sustainability for urban and regional water resources management is not a new topic. Scholars have developed many frameworks and indicators to measure sustainability of systems and their components (Loucks & Gladwell 1999; Kjeldsen & Rosenberg 2001; Sandoval-Solis et al. 2011). The American Society of Civil Engineers defines sustainable water resources as those "designed and managed to fully contribute to the objectives of the society, while maintaining their ecological, environmental and hydrological integrity, and meeting the demands to the system without its degradation, now and in the future" (American Society of Civil Engineers & UN/IHP 1998). Heaney et al (2000) defined principles for sustainable urban water systems, including minimizing system inputs for supply, minimizing export of wastes, providing economic incentives to promote demand management, using life-cycle costs to assess new development, and taxing automobile use to reflect its role in degrading environmental quality. Novotny et al (2010) comprehensively describe planning and evaluation for all aspects of the urban water cycle to create more sustainable cities of the future. While plenty of research exists regarding sustainable water resources management, it has not become engrained in planning and practice for urban water resources.

6 Discussion: Emerging of Themes in Urban Water Infrastructure

This analysis identified how dominant trends through eras of urban water infrastructure emerged from the collective influence of social, economic, health, technological and environmental factors, summarized in Table 5. For early American cities, small populations combined with political resistance to public spending and limited scientific and technological knowledge to create many small-scale, private efforts for providing urban water. The largest city in the country at the time, Philadelphia, was the first to municipalize water delivery with its small (and inefficient) Center City Water Works in 1801 (Blake 1956). As cities grew through the nineteenth century, greater population densities increased fire hazards and epidemics. These two "scourges," combined with growing capital resources, drove Progressive Era cities to fund large-scale water importation projects and adopt or adapt from new European technologies for drinking water treatment (filtration and chlorination).

Table 5: Innovations across eras of water infrastructure in the U.S. The primary drivers and funders of innovation are noted between municipal, state, and federal governments

Period	Innovations	Drivers	Funding Source
1800-1880	• Conveyance infrastructure for bringing water from *local and regional* sources • Pumping • Storage	Municipal (often through private companies)	Municipal
1880-1930	<u>Water Supply</u> • Conveyance infrastructure to bring water from *distant* sources • Treatment: Slow-sand filtration (Europe) and rapid-sand filtration (U.S.) • Disinfection: Chlorination • Regional storage <u>Sewage</u> • Widespread underground conveyance and removal	Municipal (increasing municipal controls through the Progressive Era)	Municipal
1930-1948	• Federal capital for large-scale public works • Dams and water storage • Municipal treatment for medium and small cities • Growth of bureaucracies	Federal (Investments from Great Depression and World War II)	Federal
1948-1982	• Federal water quality legislation (1948, 1961, 1965, & 1972) • Inter-region storage and conveyance • Environmental awareness • State funding • Multi-stage water treatment • Stormwater treatment	Federal	Municipal and State
1982-present	• Conservation programs • Expanding options for cost-effective treatment • Reuse and desalination • Groundwater recharge	Municipal and State	Municipal

Following World War II, wide adoption of the automobile, federal mortgage policies, and the exodus of middle class residents from central cities raised the unit costs for municipal service delivery in an ever-expanding region of low-density urbanization. The subsequent rise of environmentalism and the emergence of an increasingly post-industrial economy through the 1960's, 70's, and 80's led to environmental quality regulations, even as cities faced high costs for treating sewage outflows, maintaining existing infrastructure, and dealing with new concerns from chlorination and other treatment methods.

What trends drive today's changes in urban water infrastructure and management? I identify five key trends (Table 6). First, cities are increasingly recognizing the threat of climate variability and resource scarcity. Many wealthier cities are re-tooling policies to emphasize energy and water self-sufficiency, which can decrease importation needs. The effect of self-sufficiency on reliability is still in question. Resilience (in its many conceptions) for urban and infrastructure management is a planning priority given more infrequent but potentially catastrophic events (Hodson & Marvin 2009; Arjen et al. 2010). Since 2000, a uniquely-timed combination of concerns over terrorism, resource scarcity, and climate variability has forced cities to consider the damages that may result from rare events. Transitioning built infrastructure of past eras to deal with newly recognized threats is a long and difficult process.

Second, interest is growing in cross-disciplinary planning processes. Integrated design in buildings, community-based planning, and collaborative design sessions, called charrettes, are examples of processes where builders, planners, and administrators can integrate expert-based planning with community involvement and break down bureaucratic silos that compartmentalize duties.

Table 6: Emerging Concepts in Urban Water Infrastructure Development

Concept	Driving Factors
Integration: Longer-term planning across water, wastewater, and stormwater sectors	- Rise of integrated management approaches - Resource scarcity and climatic variability - Increasing management costs and need to identify multiple benefits for new projects - Recognized drawbacks of centralization and compartmentalization - Regulatory policies - Cost efficiencies in planning and delivery
Hybridization: Combining centralized and distributed approaches in design (infrastructure measures) and management (expert institutions & community involvement)	- Large debt-burdens from capital-intensive infrastructure, forcing a reconsideration of past approaches - Opportunity to externalize costs for stormwater management and conservation to private sector through building codes
Resilience: Self-sufficiency, portfolio approaches, and risk-based planning for uncertain events, both chronic and acute, that can affect urban water systems.	- Long-term (droughts) and short-term (floods) climatic variability - Maintenance and outages - Catastrophic events that can cause large economic damages - Insecurity of existing resources and reduced availability of new water sources to support economic growth - Rise in crisis-related narratives
Cities as Innovators: Cities will continue to lead innovation in urban water management approaches, similar to nineteenth and early twentieth century. Cities have often provided the majority of funding (except 1930-1950), but were not always drivers of innovation.	- Reduced federal funding and environmental regulatory involvement - Growth of cities as metropolitan regions and economic engines - Greater flexibility in city governments to solve problems - Political paralysis at the national level regarding long-term climate issues - Revitalization of U.S. cities and resident calls for greater sustainability - Ability to use local building codes to externalize government spending on treatment and conservation
Complex Systems: Understanding water infrastructure as complex networks with social, technical, and environmental components, which can yield emergent properties and have cascading effects	- Rise of complex systems science and network-based analysis - Recognized opportunity to use management of network for increased flexibility - Rise of *big data,* with better visualization and analysis tools - Opportunities for real-time management - Predominant tendency to look to latest technology and innovation for solving environmental problems

Third, cities will likely continue to lead innovations in urban water. In the past two centuries, except for the period of the Great Depression and World War II, cities have dominated urban water funding and innovations. After cities secured good water supplies, however, they did not immediately adopt sewage treatment. Instead, federal government mandates and funding spurred broader use of sewage treatment. New regulations, the creation of the federal EPA, and greater involvement of state governments addressed the environmental externalities presented by wastewater treatment. Today, though, federal government funding for municipal infrastructure, including water, will likely continue to decrease. Moreover, the threats of climate variability and water scarcity have significant economic affects. Cities will seek alternative funding sources and externalize some costs of updating stormwater systems through building codes.

Fourth, new tools for systems analysis can influence new design and management strategies. Growing interest in the structure and function of complex networks, including both social and technological networks, is fueling technologies that focus on aggregated analysis of component actions. Computing power and *big data* analysis is driving research to understand how systems can increase efficiency, reliability and performance. The application of evolutionary systems theory to cities provides language to understand the formation and behavior of complex urban systems that are both centrally planned and have emergent properties (Bettencourt et al. 2007).

Finally, the revitalization and gentrification in many American cities has stimulated municipal interest in the science of urban ecology and practice of landscape design. These influences drive new approaches for urban sustainability that link urban lifestyles with a more aesthetically-pleasing urban environment.

These emerging themes are influencing urban water management in several ways. Cities are developing longer-term plans that integrate across sectors (water, wastewater, stormwater, and energy) to reduce dependency on external resources. Integrated planning procedures seek cost reductions by eliminating redundant services and reformulating the flows of water in the city. In addition, resource scarcity and self-sufficiency are driving a focus on resilience and a "portfolio" approach to managing water. Conservation is a short-term solution for climatic variability, but conservation can create long-term fiscal imbalances for municipal agencies that rely on delivery revenues to fund system operation under certain rate structures. A portfolio of water supply options provides flexibility, while a portfolio of flood control measures can reduce damages from more frequent damaging events.

Cities are also considering hybrid approaches for managing water that integrate central services with distributed measures. Stormwater systems are more advanced in this regard than drinking water or wastewater. In stormwater, Low Impact Development (LID) approaches, which are technology-based and distributed, seek to reduce runoff pollution and/or increase groundwater recharge. The success of LID is closely related to the hydrology and geology of a region. Rainwater harvesting and on-site treatment are other examples of distributed approaches that depart from the traditional centralized system. Cities building new systems have the advantage of a "clean slate," which allows more freedom for new designs. When integrated with existing centralized systems, distributed infrastructure approaches may help to reduce resource use, system costs, and environmental pollution. Some tradeoffs still exist, such as reduced economies of scale or increased risk of disease through mosquito populations that breed in standing water. Continued research must address issues of reliability, public health, funding, and maintenance for evolving system designs. Shrinking state and federal budgets are also forcing cities to identify new funding streams that incorporate multiple environmental and economic benefits.

Finally, expert-driven, technocratic water management is again being challenged in favor of more open planning processes with community involvement. Yet, technological solutions will still be important, especially new treatment technologies and computing. Technologies may also facilitate data collection to identify system failures or help monitor water use.

7 Conclusions

Urban water infrastructure in North America has progressed through several eras. First, private companies were granted charters to provide water in smaller cities of low population density. Companies exploited groundwater resources and nearby springs, using a labor-intensive network of water carriers to move poor-quality water to urban users. Next, cities municipalized water infrastructure and built larger projects that reached to more distant sources of cleaner water to combat fire, improve health, and promote economic development. The influx of water imports caused a wastewater crisis. In response, cities built large-scale, underground sewer projects to convey sewage out of city centers. They also capitalized on new treatment technologies to augment imports, improve local storage capabilities, and reduce disease. Larger systems also required innovations in management. Expert-based administrators and sanitary engineers centralized water supply and wastewater duties, using debt-financing and taxation to shift responsibility from individuals to trained experts. Following World War II, the growth of low-density suburbs changed the economics of water provision and removal, increasing delivery costs of municipal services to an ever-expanding urban periphery. Environmentalism in the 1960's and 70's spurred state and federal environmental mandates, which was institutionalized through drinking water standards and point-source discharge permits. Finally, the rise of sustainability and growing recognition of resource scarcity is currently driving cities to consider self-sufficiency, integrated management of water, and portfolio approaches that provide greater flexibility.

Several ideas in urban water management are emerging. Cities will continue to seek greater self-sufficiency, especially in arid climates. They will also work to develop more flexible infrastructure designs that increase flexibility to respond to chronic (long-term drought) or acute (hurricanes, floods) events. Hybridization in both the design (distributed and centralized approaches) and management (community and expert involvement) will likely grow to meet environmental regulations and reduce costs. Finally, new technologies will be important. Increased data collection and analysis capabilities will help cities identify failures and provide greater flexibility to move water in time and space more efficiently. In addition, new treatment technologies will promote innovative reuse and recharge schemes. Yet, as shown through urban environmental history studies, many of the same questions for urban water persist regarding use, reuse, waste, and supply. Urban environmental history provides an important backdrop to inform planning and reveal the interconnected nature of environment processes, social actions, and the success of new technological approaches.

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Chapter 3

Target-Based Optimization of Stormwater Infrastructure in an Urban Region

> *The commission accepted that the cost-benefit analysis could never include all the factors relevant to the decision. But it could provide a framework within which all the evidence could be brought together and weighed. In fact, the final verdict of the majority of the commissioners could be fairly described as cost-benefit analysis modified by judgment.*
>
> - Sir Peter Hall, Great Planning Disasters

Abstract

Cities manage stormwater runoff using infiltration and conveyance. Dominant stormwater management strategies vary *among* and *within* cities based on: environmental and landscape characteristics; economics; available technologies; and regulatory policies. This chapter presents a theoretical model to optimize stormwater allocations in a metropolitan region. It uses a simplified construct of an urban region to reveal relationships in key variables, which can then be applied to analyze metropolitan areas with recognizable economic and geographic diversity. The model identifies the low-cost mix of conveyance (surface channels and sewers) and infiltration (landscape, large-scale basins, and Low-Impact Development (LID)/green infrastructure) to satisfy design-storm removal requirements. It illustrates how changes *within* cites, including land values and surface cover, affect allocations and total costs across the metropolitan region. It also compares dominant strategies *among* cities with variable rainfall, soil infiltration rates, treatment requirements, and infrastructure costs. Results provide several insights. First, unit costs of removal are highest in downtown areas due to property values, while total costs are higher in suburban areas due to greater land area. Second, dominant strategies in each region are closely related to land costs. In downtown areas, high land costs make sewers cost-effective, while in suburbs, surface channels are more cost-effective because they convey more water and land costs are lower. In the city outskirts reduced impervious surface area makes the "free" strategy of landscape infiltration dominant. Third, rainfall and soil infiltration parameters significantly affect total system costs. Total costs increase as average rainfall rates increase or soil infiltration rates decrease. Fourth, in expensive cities, sewers are cost-effective throughout the region. Finally, LID/green infrastructure becomes competitive as its unit construction costs decrease if cities implement it without accruing land costs (i.e. on public lands). This also drives mandates for LID on private lands. The theoretical framework is adaptable to cities of varying geography, geology, and climate. The analysis describes key drivers for emerging urban stormwater management trends and illustrates the critical role of environmental characteristics for stormwater system design.

1 Introduction

Urban stormwater management traditionally emphasized conveyance and storage of runoff to reduce flood risks. Today, cities in industrialized countries face challenges of aging sewers and surface channels, which require capital investments and maintenance to meet increasingly stringent pollution control requirements. This often means expensive new treatment plants and underground storage facilities to prevent contaminants from directly entering local surface and groundwater sources. In many older cities, stormwater and sewage drain through the same pipes in combined systems. This can lead to Combined Sewer Overflows (CSOs) during large storms, when runoff volume overwhelms system capacity, causing discharges of untreated sewage to local water bodies. Newer cities without combined sewers do not have this specific problem, but often face related environmental quality problems such as contaminated surface and groundwater.

While investments in existing stormwater infrastructure continue, cities are also increasing infiltration in landscapes to reduce runoff and pollution. Best Management Practices (BMPs), Low-Impact Development

(LID), green infrastructure, Sustainable Urban Drainage Systems (SUDS), and Water Sensitive Urban Design (WSUD) all describe innovative approaches to managing stormwater that reduce the velocity and quantity of urban runoff, making cities more closely emulate the hydrologic characteristics of less-disturbed landscapes (Low Impact Development Center 2000; EPA 2008; Center for Watershed Protection 2011). For flood-prone cities, low-lying regions can combine these innovative approaches with better land-use planning to minimize the hazards of building in floodplains. A challenge for future stormwater designs is to combine natural, engineered, and policy elements that minimize flood risk while also reducing environmental contamination from runoff.

This research aims to answer several key questions regarding metropolitan stormwater management. First, how does the cost-effective mix of existing and innovative stormwater actions vary throughout an urban region? Second, how do environmental parameters affect optimal decisions? Third, how do emerging regulatory and maintenance requirements affect decisions? Finally, under what conditions does LID become cost-effective?

The paper presents an integrative decision model to explain how cost-effective stormwater infrastructure decisions change throughout a metropolitan region. It demonstrates how city size, rainfall and infiltration, green infrastructure costs, and treatment and maintenance requirements affect stormwater design decisions. It uses a typical framework for runoff target requirements to determine stormwater infrastructure capacity. The model illustrates how: 1) land costs and imperviousness affect dominant stormwater strategies *within* cities, and 2) changes in environmental and technology patterns influence different strategies *among* cities. It captures a more integrated view of future stormwater management that links engineering practice with economic, environmental, regulatory, and social considerations.

2 Background

Urban regions alter the timing, duration, and velocity of stormwater runoff by increasing impervious surface area (Hollis 1975; McCuen 1979; Duncan 1995a; Zoppou 2001; Shuster et al. 2005). Urbanized regions also increase pollution in local watersheds (Ellis 1986; Duncan 1995b; Brabec et al. 2002). Stormwater systems in many industrialized cities were developed in the early- and mid-20th century (Tarr 1984). They typically augment reduced infiltration capacity of urban landscapes by conveying runoff in sewers and surface channels. Today, however, stormwater infrastructure must also minimize watershed contamination. Stormwater runoff carries a mix of oils, greases, metals, pesticides, nitrates, phosphates, and pharmaceuticals (Whipple 1983; Moore et al. 1984; Ellis 1986; Huber 1992; Duncan 1995b). Limited research has explored how traditional structural stormwater measures combine with newer techniques to meet evolving regulatory and cost challenges. Moreover, research must further compare how land use, infrastructure costs, and environmental conditions influence the viability of innovative measures for stormwater planning (Sample et al. 2001).

In the U.S., municipal stormwater permits for both separate and combined sewer systems specify actions that cities must take to reduce pollution from stormwater runoff. Regulations began with the federal Clean Water Act and expanded through court rulings (U.S. Code 1987; EPA 1999). In the law, however, the U.S. Congress also recognized the large and potentially prohibitive costs many communities face to meet numerical limits for stormwater contaminants. Instead, the law requires communities to develop pollution reduction plans. In California, federal law is augmented by a Superior Court ruling to mandate stormwater plans that use Best Management Practices:

> Congress has determined that it is not feasible at this time to establish numeric effluent limits for pollutants in storm water discharges from MSFs [Clean Water Act (CWA) Section 402(p)(3)(B)(iii)]. In addition, the California Superior Court ruled; "*Water quality-based effluent limitations are not required for municipal Stormwater discharges [33 USC§1342(p)(3)(B)] and [40 CFR§122.44(k)(3)]. For municipal stormwater discharges, the Permits must contain best management practices (BMPs), which reduce pollutants to the maximum extent practicable* (CV-RWQCB 2007).

Communities are required to reduce stormwater pollution by the Maximum Extent Practicable (MEP) and they detail their strategies to regulators through municipal stormwater permits. The federal and state guidance provides strong incentives for communities to promote stormwater systems that substitute BMPs for expensive new treatment facilities.

The cost-effectiveness of management options for future urban stormwater infrastructure decisions depends on many factors. First, biogeophysical characteristics of the urban environment influence the viability of infiltration-based management. Cities with less-permeable soils must identify particular areas where infiltration is viable. On the other hand, cities with more permeable soils can utilize more infiltration, especially for small- and medium-sized storms. Second, hydrologic characteristics of regions influence the need for landscape-based water storage and pollution removal. Cities with many days of precipitation in a year (>150) require more robust stormwater infrastructure. Third, population density and land values influence the use of conveyance and infiltration. Fourth, the presence of existing infrastructure affects technology and economics of new designs. In particular, cities with combined sewers must update stormwater management systems to prevent CSOs. Fifth, internal and external regulatory requirements and penalties often force cities to consider new management options. Finally, social attitudes influence the adoption of new approaches. Combined, these factors drive urban stormwater management decisions. Moreover, system managers weigh factors in the context of their expertise and preferences. Understanding and describing this complex set of influences through a simple modeling approach offers conceptual insights for integrated urban stormwater design.

Costs for building and operating urban water infrastructure throughout a metropolitan region also vary based on metropolitan geography. Past approaches used operations research techniques and simplified models of urban structure to describe tradeoffs in economics and geography for many types of infrastructure. For instance, Clark and Stevie (1981) identified spatial dependencies in total system costs for regional water supply delivery based on system size. Utilities lower unit costs by serving more people while also keeping the service area small to limit distribution costs. Across the metropolitan region, centripetal factors that favor water sources near demands (capital and operating costs for pipeilnes) combine with centrifugal factors (land acquisition costs, source elevations, and location of high-quality water sources in the metropolitan region) to influence the utility service areas and the predominant location of water sources (Lund 1990). For stormwater, similar tradeoffs exist between unit costs of construction, which correspond with land scarcity, and total removal capacity requirements, which grow as land area increases.

2.1 Hypothesis: Stormwater costs throughout the metropolitan region

Cost-effective stormwater actions vary across a metropolitan region with economics, population density, and environmental characteristics. Sewers are likely more cost effective near dense downtown areas where land values prohibit extensive development of surface channels. Farther from the city center, surface measures such as conveyance and infiltration are more viable. Eventually, landscape infiltration becomes dominant as more pervious land area is available. LID can decrease stormwater system management costs by reducing the necessary capacity of sewers and channels when no land acquisition costs are incurred. Figure 1 illustrates how unit costs vary across a hypothetical metropolitan region for different stormwater actions.

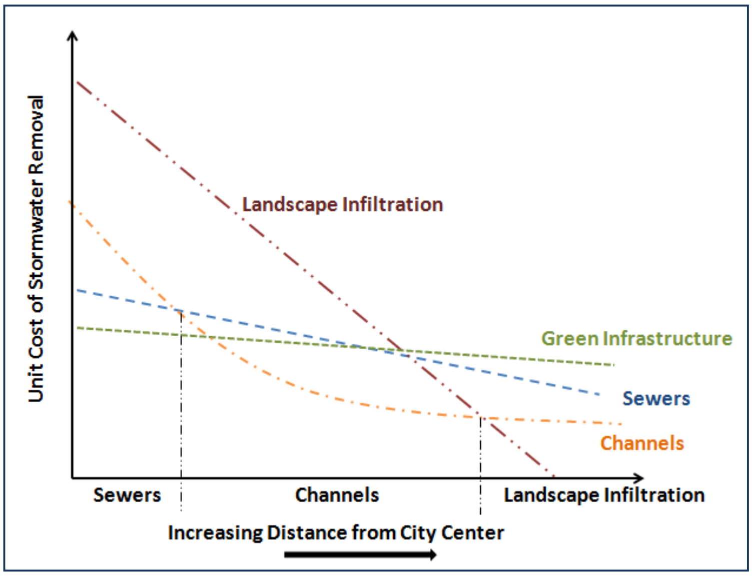
3 Model Formulation and Decision Variables

I developed a linear programming formulation to evaluate how environmental, economic, and engineering factors influence cost-effective allocations of stormwater infrastructure across a metropolitan region. The model minimizes the total cost of building infrastructure to meet requirements for stormwater removal capacity throughout the region using a mix of five possible measures:

1) **Underground sewers**, which have higher unit construction costs and smaller capacities, but do not require dedicated surface area with land acquisition costs. Sewers have long-term water treatment and maintenance costs;
2) **Surface channels**, which have greater capacity but incur land costs to secure rights-of-way. Channels have long-term water treatment and maintenance costs;
3) **Landscape infiltration** occurs as a "free" ecosystem service, but has reduced capacity to remove rainfall in urban areas with impervious surfaces. Landscape infiltration does not incur treatment or maintenance costs, but is subject to limitations of soil infiltration rates.
4) **Local retention basins** represent distributed LID measures in the model. The terms LID and green infrastructure are used interchangeably throughout the text and refer *only* to local retention basins. LID has construction and long-term maintenance costs, but no costs for water treatment. LID can enhance the retention and infiltration capacity of existing landscapes;
5) **Large-scale stormwater capture and infiltration basins**, which can lower construction costs for stormwater capture through economies of scale as compared to LID. They are often built in areas of higher soil infiltration rates and use injection wells to recharge water directly to aquifers. Large-scale infiltration basins, though, require significant contiguous land areas.

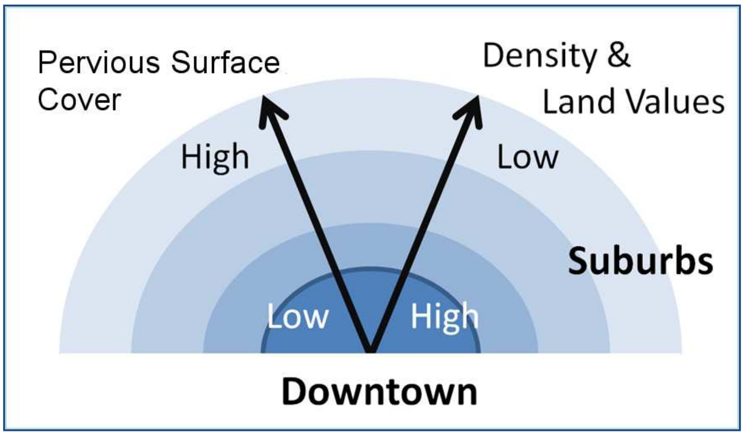
The model minimizes the total costs of building stormwater removal infrastructure to meet design targets based on costs for 1) land acquisition, 2) construction, 3) stormwater treatment, and 4) operations and maintenance. Figure 1 illustrates the hypothesized distribution of unit costs of removing stormwater for different strategies.

Figure 1: Theoretical distribution of cost-effective stormwater measures throughout the metropolitan region. Near the dense city center, sewers are cost effective because of high land costs. Farther from the city center, channels dominate because they can convey more water. Far from the city center in areas with more permeable land cover, infiltration becomes dominant. Green infrastructure may reduce the unit costs of existing measures by substituting for sewers or channels in different parts of the urban region.



I used a hypothetical urban region to formalize equations that represent changes in economic and environmental parameters across different parts of a city. Stylized models of urban areas have represented cities using concentric rings to delineate regions of decreasing land value surrounding a central downtown area (von Thünen 1826; Alonso 1960). While originally developed to explain urban development patterns, such models may be useful today as instructive simplifications of metropolitan structure, which help to identify key relationships. In the simplified urban model for this analysis, land values, density, and impervious surface cover decreased with distance from the city center, while infiltration capacity increased (Figure 2). Relationships identified by the analysis can be adapted at finer scales using real-world geographic data to simulate more varied and complex urban forms. Land values, infrastructure, and other social and environmental factors are all examples of parameters that may not be purely linear or exponential throughout the metropolitan region (Anas et al. 1998; Cadenasso et al. 2007; Batty 2008; Marshall 2009).

Figure 2: Diagram of hypothetical urban region. Land values and density decrease with distance from center, while pervious surface cover increases



The analysis first optimized allocations throughout the region for the base case: a new city without infrastructure. It then extended the base case through a sensitivity analysis to test how changes in environmental, regulatory, and cost factors affect optimal designs.

Decision variables (in bold below) determine the area devoted to physical infrastructure at a distance *r* for sewer pipes $(A_S(r))$, surface channels $(A_C(r))$, large-scale infiltration basins $(A_{MI}(r))$, and distributed LID measures $(A_{LID}(r))$. The area determines the costs associated with building and maintaining infrastructure. Further, the area in combination with pipe and channel geometry, determines the conveyance capacity. For infiltration in large-scale basins and distributed retention ponds (LID), the model calculates total costs and drainage capacity by knowing the area allocated to each action. The remaining land area is devoted to on-site landscape infiltration or impervious surfaces.

The total costs, Z, include costs for sewers (C_S), surface channels (C_C), and infiltration (C_I), across the semi-circular metropolitan region with a radius of *R*. The costs for each measure depend on the amount constructed:

$$Min\ Z = \int_0^R \Big(C_S(r, \boldsymbol{A_S(r)}) + C_C(r, \boldsymbol{A_C(r)}) + C_I\big(r, \boldsymbol{A_{MI}(r)}, \boldsymbol{A_{LID}(r)}\big)\Big)\, dr \tag{1}$$

The model divided the entire region into ten sub-regions of specified width and increasing area to create concentric rings around the city center. The distance from the city center to the edge of a ring is equal to *r*.

Total costs for each stormwater measure include construction, C_N, and maintenance, C_M. In addition, surface such as channels and infiltration have land acquisition costs, C_L. Finally, sewers and channels have costs for treating runoff, C_T, while infiltration measures do not have treatment costs.

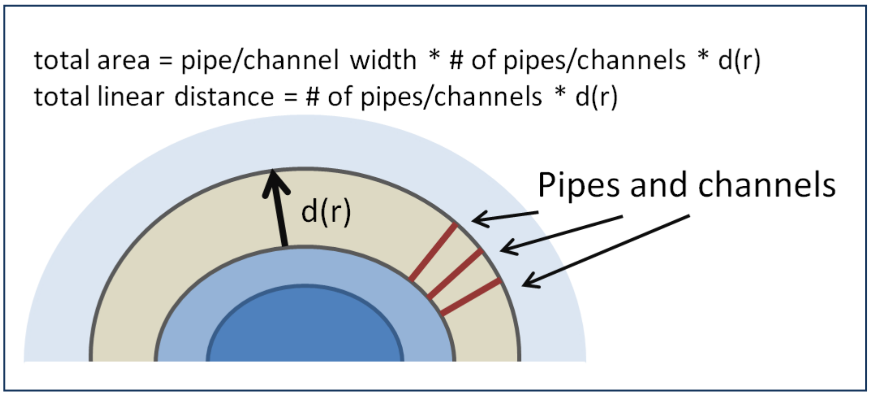
$$Sewers: \quad C_S(r, \boldsymbol{A_S(r)}) = C_{N_S}(r, \boldsymbol{A_S(r)}) + C_{T_S}(r, \boldsymbol{A_S(r)}) + C_{M_S}(r, \boldsymbol{A_S(r)}) \tag{2}$$

Channels: $$C_C(r, \boldsymbol{A_C}(\boldsymbol{r})) = C_{N_C}(r, \boldsymbol{A_C}(\boldsymbol{r})) + C_{T_C}(r, \boldsymbol{A_C}(\boldsymbol{r})) + C_{M_C}(r, \boldsymbol{A_C}(\boldsymbol{r})) + C_{L_C}(r, \boldsymbol{A_C}(\boldsymbol{r})) \tag{3}$$

Infiltration: $$C_I(r, \boldsymbol{A_{MI}}(\boldsymbol{r}), \boldsymbol{A_{LID}}(\boldsymbol{r})) = C_{N_I}(r, \boldsymbol{A_{MI}}(\boldsymbol{r}), \boldsymbol{A_{LID}}(\boldsymbol{r})) + C_{M_I}(r, \boldsymbol{A_{MI}}(\boldsymbol{r}), \boldsymbol{A_{LID}}(\boldsymbol{r})) + C_{L_I}(r, \boldsymbol{A_{MI}}(\boldsymbol{r})) \tag{4}$$

Total construction costs for each possible stormwater measure are based on unit costs. For sewers and channels, unit costs $\left(K_{N_S}(r), K_{N_C}(r)\right)$ are assessed per linear foot. To determine the length of each measure in a region, the model selects decision variables for the area of sewers and channels, divides them by the specified width of pipes/channels to calculate the number of pipes/channels spanning the region, and then multiplies the number of pipes/channels times the linear distance $(d(r))$ of that region to calculate the total length of each structural action. The formulation assumes that pipes and channels are dispersed throughout the region. Figure 3 illustrates the procedure for calculating the length of conveyance.

Figure 3: Illustrated method for converting decision variables of total area for sewers and channels in each region to a linear distance, which is used to calculate costs. The total area for conveyance in a region through sewers and channels is assumed to be dispersed throughout the region and span its length ($\boldsymbol{d(r)}$). Dividing the area of pipes and channels by the assumed widths gives the number of pipes and channels in a region.



3.1 Construction Costs

For sewers, the total construction costs $\left(C_{N_S}(r, \boldsymbol{A_S}(\boldsymbol{r}))\right)$ are made of only unit construction costs. For surface channels, total construction costs $\left(C_{N_C}(r, \boldsymbol{A_C}(\boldsymbol{r}))\right)$ include both construction and land acquisition. For infiltration, total construction costs $\left(C_{N_I}(r, \boldsymbol{A_{MI}}(\boldsymbol{r}), \boldsymbol{A_{LID}}(\boldsymbol{r}))\right)$ include both large-scale infiltration $\left(C_{N_{MI}}(r, \boldsymbol{A_{MI}}(\boldsymbol{r}))\right)$ and LID $\left(C_{N_{LID}}(r, \boldsymbol{A_{LID}}(\boldsymbol{r}))\right)$. Large-scale infiltration measures include costs for land and construction, while LID measures only include construction costs, since cities often implement LID measures on public lands to forgo land costs. Equations 5-9 specify these calculations.

Sewer Construction: $$C_{N_S}(r, \boldsymbol{A_S}(\boldsymbol{r})) = \left(\frac{d(r) * \boldsymbol{A_S}(\boldsymbol{r})}{W_S(r)}\right)\left(K_{N_S}(r)\right) \tag{5}$$

Channel Construction: $$C_{N_C}(r, \boldsymbol{A_C}(\boldsymbol{r})) = \left(\frac{d(r) * \boldsymbol{A_C}(r)}{W_C(r)}\right)\left(K_{N_C}(r)\right) + \left(\boldsymbol{A_C}(r)\right)\left(K_L(r)\right) \tag{6}$$

Infil. Constr.: $$C_{N_I}(r, \boldsymbol{A_{MI}}(\boldsymbol{r}), \boldsymbol{A_{LID}}(\boldsymbol{r})) = C_{N_{MI}}(r, \boldsymbol{A_{MI}}(\boldsymbol{r}) + C_{N_{LID}}(\boldsymbol{A_{LID}}(\boldsymbol{r}))) \tag{7}$$

MI Construction: $$C_{N_{MI}}(r, \boldsymbol{A_{MI}}(\boldsymbol{r})) = \boldsymbol{A_{MI}}(\boldsymbol{r}) * \left(K_{N_{MI}}(r) + K_L(r)\right) \tag{8}$$

LID Construction: $$C_{N_{LID}}(r, \boldsymbol{A_{LID}(r)}) = \boldsymbol{A_{LID}(r)} * \left(K_{N_{LID}}(r)\right) \quad (9)$$

3.2 Maintenance Costs

The model assesses maintenance costs for sewers, channels, large-scale infiltration, and LID measures based on unit costs that are annualized over 20 years. A multiplication factor, β is used to calculate the total value in present-day dollars of annual maintenance costs, C_{OM}, over a period of *n* years, based on an assumed inflation rate *b* and an interest rate *i* (Collier & Ledbetter 1988):

Present Value of Maintenance Costs: $$PV = C_{OM} * \beta = C_{OM} * \left(\frac{\left(\frac{1+b}{1+i}\right)^{n} - 1}{r - i}\right) \quad (10)$$

Unit costs are assumed to be a percentage of construction costs adapted from available research. The total maintenance costs for each action are calculated using equations 11-15.

Sewer Maintenance Costs: $$C_{M_S}(r, \boldsymbol{A_S(r)}) = \left(\frac{d(r) * \boldsymbol{A_S(r)}}{W_S(r)}\right)\left(K_{M_S}(r)\right) * \beta \quad (11)$$

Channel Maintenance Costs: $$C_{M_C}(r, \boldsymbol{A_C(r)}) = \left(\frac{d(r) * \boldsymbol{A_C(r)}}{W_C(r)}\right)\left(K_{M_C}(r)\right) * \beta \quad (12)$$

For infiltration, only large-scale basins and LID sites have maintenance costs:

Infiltration Maintenance: $$C_{M_I}(r, \boldsymbol{A_{MI}(r)}, \boldsymbol{A_{LID}(r)}) = C_{M_{MI}}(r, A_{MI}(r)) + C_{M_{LID}}(r, A_{LID}(r)) \quad (13)$$

MI Maintenance: $$C_{M_{MI}}(r, \boldsymbol{A_{MI}(r)}) = \boldsymbol{A_{MI}(r)} * K_{M_{MI}}(r) * \beta \quad (14)$$

LID Maintenance: $$C_{M_{LID}}(r, \boldsymbol{A_{LID}(r)}) = \boldsymbol{A_{LID}(r)} * K_{M_{LID}}(r) * \beta \quad (15)$$

3.3 Treatment Costs

The model assesses annualized treatment costs for sewers, $C_{T_S}(r)$, and channels, $C_{T_C}(r)$, by multiplying the total design flow capacity of each conveyance option by the annualized cost of building treatment plant facilities. No infiltration measures incur treatment costs, as cities assume that the soil breaks down contaminants. While increased use of landscape infiltration may create long-term pollution issues with costs for remediation, the model simulates the present situation.

Treatment Costs for Sewers: $$C_{T_S}(r, \boldsymbol{A_S(r)}) * = Q_S(r, \boldsymbol{A_S(r)}) * K_T * \beta \quad (16)$$

Treatment Costs for Channels: $$C_{T_C}(r, \boldsymbol{A_C(r)}) = Q_C(r, \boldsymbol{A_C(r)}) * K_T * \beta \quad (17)$$

3.4 Removal Capacity

The model calculates total removal capacity using standard equations for flow and infiltration. The total removal capacity, Q_T, is equal to the sum of removal capacities for each measure across all regions. Removal capacity must be greater than or equal to the target design flow based on runoff from the 85^{th} percentile rainfall volume for each region. Sewer flows, $Q_S(r)$, are calculated using Manning's equation for unpressurized pipe flow. Channel flows, $Q_C(r)$, are calculated using Manning's equation for open-channel flow with a cross-sectional area of A_{CS}, a roughness coefficient *n*, and a hydraulic radius and slope. Infiltration flows are calculated for each type of infiltration measure based on the total allocated area and the associated infiltration rate for large-scale basins (i_{MI}), LID (i_{LID}), and permeable landscapes (i_L). Infiltration rates are higher in the large-scale basins and LID areas by design. Impervious surface area in each region, $I(K_L(r))$, is a function of distance from the city center (see Section 4.5). Equations 18-22 list the flow calculations.

Total Removal: $$Q_T = \int_0^R (Q_S(r) + Q_C(r) + Q_I(r))\, dr \quad (18)$$

Removal Per Region: $$Q_S(r, \boldsymbol{A_S(r)}) + Q_C(r, \boldsymbol{A_C(r)}) + Q_I(r) \geq Q_{design}(r) \quad (19)$$

Sewers: $$Q_S(r, \boldsymbol{A_S(r)}) = \left(\frac{.463}{n}\right)\left(\frac{H}{P}\right)^{8/3} (S(r))^{1/2} \quad (20)$$

Channels: $$Q_C(r, \boldsymbol{A_C(r)}) = \left(\frac{1.49}{n}\right) A_{CS}(R)^{2/3}(S(r))^{1/2} \quad (21)$$

Infiltration: $$Q_I(r, \boldsymbol{A_{MI}(r)}, \boldsymbol{A_{LID}(r)}) = i_{MI}\, \boldsymbol{A_{MI}(r)} + i_{LID}\, \boldsymbol{A_{LID}(r)} + i_L \left(\boldsymbol{A_{LI}(r)} * \left(1 - I(K_L(r))\right)\right) \quad (22)$$

The combined area for infiltration, surface conveyance, and other land (buildings, roads, etc) in a region cannot exceed the total area of that region:

$$\boldsymbol{A_{total}(r)} = \boldsymbol{A_C(r)} + \boldsymbol{A_{MI}(r)} + \boldsymbol{A_{LID}(r)} + \boldsymbol{A_{LI}(r)} + \boldsymbol{A_O(r)} \quad (23)$$

Finally, non-negativity constraints are applied to all decision variables. Table 1 gives the complete list of variables included in the model.

Table 1: List of variables included in the model

Variable	Description	Symbol
Primary decision variables: Area		
Sewers Area	Total area (underground) for sewer conveyance in a region of the metropolitan area. Used to calculate total pipe length	$A_S(r)$
Channels Area	Total area for surface conveyance in channels in a region of the metropolitan area. Used to calculate total channel length	$A_C(r)$
Large-Scale Infiltration Area	Total area for large-scale infiltration basins in a region of the metropolitan area	$A_{MI}(r)$
Low-Impact Development (LID) Area	Total area for LID/green infrastructure measures, modeled as retention ponds, in a region of the metropolitan area. LID strategies would assume to be dispersed throughout the landscape	$A_{LID}(r)$
Landscape Infiltration Area	Remaining portion of landscape in a region of the metropolitan area that has pervious surfaces to provide removal through infiltration	$A_{LI}(r)$

Other Land Area	Land not included in stormwater measures. Includes impervious areas in the urban landscape	$A_O(r)$
Calculated (secondary) decision variables based on area: Removal (Flow) Capacity and Costs		
Flow variables		
Sewers	Total flow capacity for stormwater removal through sewer conveyance	$Q_S(r, A_S(r))$
Channels	Total flow capacity for stormwater removal through channel conveyance	$Q_C(r, A_C(r))$
Large-Scale Infiltration Basins	Total removal capacity from large infiltration basins	$Q_I(r, A_{MI}(r))$
Low-Impact Development (LID) sites	Total removal capacity from LID measures (retention ponds)	$Q_I(r, A_{LID}(r))$
Landscape Infiltration	Total removal capacity in the landscape. This removal is considered free, but constrained by environmental limits and urban structure.	$Q_I(r, A_{MI}(r), A_{LID}(r))$
Costs		
Total System Costs	Total costs for removal	Z
Total Costs of Sewers by region	Total costs for sewer measures, including construction, treatment, and maintenance, in a region of the metropolitan area	$C_S(r, A(r)_S)$
Construction Costs of Sewers	Costs for sewer construction	$C_{N_S}(r, A(r)_S)$
Treatment Costs of Sewers	Costs for treating stormwater conveyed through sewers	$C_{T_S}(r, A(r)_S)$
Maintenance Costs of Sewers	Costs for maintaining sewers, calculated for 20-year annualized costs	$C_{M_S}(r, A(r)_S)$
Total Costs of Channels by region	Total costs for channel measures, including construction, treatment, maintenance, and land costs, in a region of the metropolitan area	$C_C(r, A(r)_C)$
Construction Costs of Channels	Costs for channel construction	$C_{N_C}(r, A(r)_C)$
Treatment Costs of Channels	Costs for treating stormwater conveyed through channels	$C_{T_C}(r, A(r)_C)$
Maintenance Costs of Channels	Costs for maintaining channels, calculated for 20-year annualized costs	$C_{M_C}(r, A(r)_C)$
Land Costs of Channels	Land acquisition costs for surface channels, based on land values in each region	$C_{L_C}(r, A_C(r)$
Total Costs for Infiltration	Total costs for all infiltration measures, including LID and large-scale infiltration basins, in a region of the metropolitan area.	$C_I(r, A(r)_{MI,}(A(r)_{LID})$
Large-Scale Infiltration Construction	Costs for construction of large-scale infiltration basins, including infrastructure and land costs	$C_{MI}(r, A(r)_{MI})$
Large-Scale Infiltration Maintenance	Costs for maintaining infiltration basins, calculated for 20-year annualized costs	$C_{N_{MI}}(r, A(r)_{MI})$
Construction Costs of LID	Costs for construction of LID measures (retention ponds)	$C_{N_{LID}}(r, A(r)_{LID})$
Maintenance Costs of LID	Costs for maintaining LID measures, calculated for 20-year annualized costs	$C_{M_{LID}}(r, A(r)_{LID})$
Parameters		
Radius	Distance of a region from the downtown center	r
Infiltration rates		
Infiltration rate in large-scale basins	Infiltration rate in large-scale basins, which are typically sites in areas of high recharge	i_{MI}

	rates	
Infiltration rate for landscapes	Based on soil characteristics. This infiltration rate is applied to all pervious areas that are not LID or large-scale basin sites	i_L
Infiltration rate in LID sites	Infiltration rate at LID sites, which are typically engineered to increase removal capacity	i_{LID}
Hydraulic parameters		
Sewer pipe diameter	Diameter of sewer pipes, assumed to be constant throughout regions	H
Manning's n	Roughness coefficient for channel and pipe flow calculations using Manning's equations	n
Slope	Slope for calculated flow in pipes and channels	$S(r)$
Hydraulic radius	Equation to the cross-sectional area of flow divided by the wetted perimeter. Used in equation for channel flow	R
Channel cross-sectional area	Cross-sectional area of channels, used in calculating channel flow	A_{CS}
Diameter (length) of a region	Linear distance (length) of the semi-circular region in the metropolitan area. Used to calculate total length of sewers and channels	$d(r)$
Economic parameters		
Inflation rate	Assumed rate of inflation used to calculate 20-year annualized costs	b
Interest rate	Assumed interest rate used to calculate 20-year annualized costs	i
Infrastructure lifespan	Time period for present value of annual costs	n
Annualized cost multiplier	Calculated value, based on interest rate, rate of inflation, and infrastructure lifespan	β
Unit Costs		
Land	Land costs, per acre, including the value of both land area and building improvements	$K_L(r)$
Sewer construction	Unit cost for building sewers, per linear foot.	$K_{N_S}(r)$
Channel construction	Unit cost for building channels, per linear foot.	$K_{N_C}(r)$
Large-scale infiltration basin construction	Unit cost for building large-scale infiltration basins, per acre-foot of flow capacity	$K_{N_{MI}}(r)$
LID construction	Unit cost for building LID sites, modeled as retention ponds, per square foot of area for a pond with a maximum depth of 5 feet	$K_{N_{MI}}(r)$
Treatment	Unit cost for building water treatment plants, based on unit costs for design flow capacities.	K_T
Sewer maintenance	Unit cost for maintenance of sewers. Present value costs of annual maintenance are calculated over 20 years.	$K_{M_S}(r)$
Channel maintenance	Unit cost for maintenance of channels. Present value costs of annual maintenance are calculated over 20 years.	$K_{M_C}(r)$
Large-scale infiltration maintenance	Unit cost for maintenance of large-scale infiltration basins. Present value costs of annual maintenance are calculated over 20 years.	$K_{M_{MI}}(r)$
LID maintenance	Unit cost for maintenance of LID sites. Present value costs of annual maintenance are calculated over 20 years.	$K_{M_{LID}}(r)$

4 Model Implementation and Parameters

Values for modeled parameters came from literature, newly-generated data, and previously existing data sets. The analysis included both a base case and a sensitivity analysis to test the effects of varying city size, average rainfall and infiltration rates, construction costs, treatment requirements, and maintenance costs. The base case included many parameters based on data for the Sacramento, CA, region, though the analysis is not intended to fully represent Sacramento stormwater systems. The sensitivity analysis built on the base case using parameter ranges that represented other North American cities. The procedures for estimating parameters are described below.

4.1 Land Values

Urban land cost may be estimated using an exponential decay function (Muth 1969), such that:

$$C = C_o \, e^{-\lambda r} \tag{24}$$

where C is the cost per unit area of property, including building improvements, C_o is the property cost at the city center including building improvements, $-\lambda$ represents the decrease in value of a parcel of land, and r is the distance between the city center and the land parcel. To test the validity of Equation 24, parcel assessment data from the city of Sacramento, CA was analyzed for an 8-mile transect from the downtown area through the eastern suburbs to the city of Folsom (Sacramento County 2013). The regression function in *Excel* was used to find a line of best fit. While a line of best fit using an exponential distribution had a relatively high R^2 value (0.59), a power law distribution had a higher R^2 value (0.93). This power law relationship was used as the "base case" and simulated the *moderate-sized* city, based on Sacramento's population characteristics, as given in Table 2.

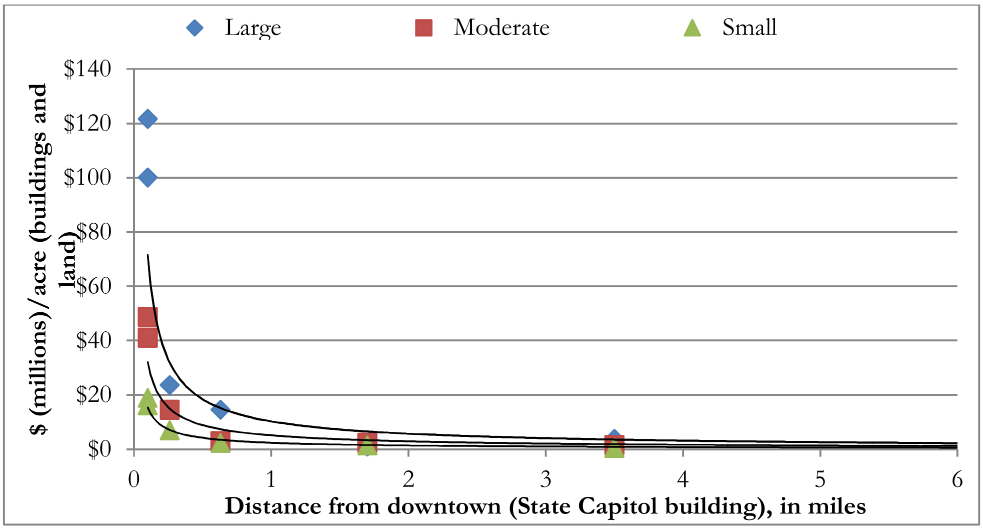
4.1.1 *Sensitivity Analysis: Varying city size and land costs*

To consider how population density and land costs affect management decisions, changes in city size were approximated by varying land values. The analysis generated a series of land values based on the base case, which simulated property costs across cities of different sizes. The distribution of land values as a function of distance from city center was extended to include higher and lower land costs (including both property and buildings), which simulated larger and smaller cities (Figure 4). This procedure assumed that larger cities have more expensive downtown areas and the distribution of land values in all cities follows a power law. For larger cities, this means that the radius of "expensive" areas extends farther through the region than in small cities. It also examined allocations in regions of the same distance (1-10 miles) from the densest area of the region, which might not capture the total metropolitan area of some larger cities. Table 2 lists the equations and corresponding R^2 values for each city size.

Table 2: Equations and corresponding R^2 values for relationships of land cost and distance to city center for the base case for the large and small cities, in relation to the base case

City Size	Changes in Relationship of Land Value (Z) and Distance (r)	R^2 value
Large	$Z = 10.28 * r^{-.842}$	.82
Moderate (base case)	$Z = 5.12 * r^{-.797}$	.93
Small	$Z = 2.42 * r^{-.801}$	.97

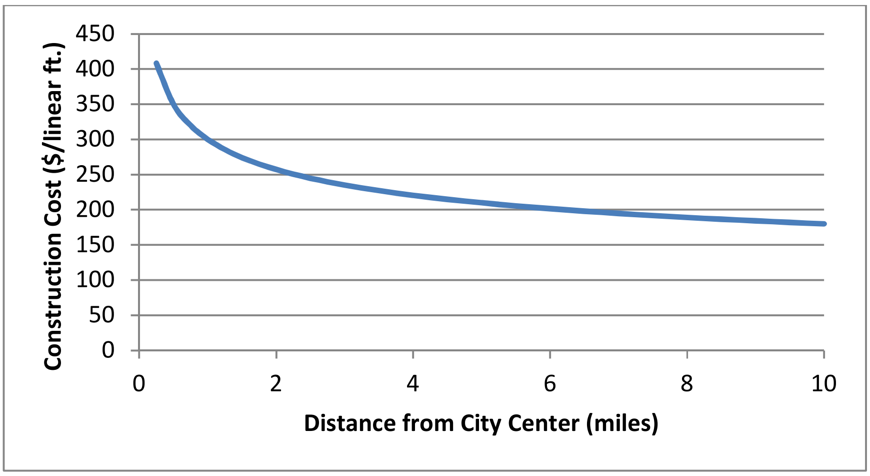
Figure 4: Costs of improved land (including property and buildings) for cities of varying sizes based on distance to downtown. The base case (moderate) reflects data from Sacramento, CA (Source: County of Sacramento).



4.2 Construction costs

Unit costs (by length) for construction of stormwater sewers vary based on density characteristics of the urban landscape (Figure 5). Close to the city center, costs are higher, representing the additional costs for digging, paving, and situating underground sewers in dense urban areas. Away from the city center, costs are lower. Unit construction costs for underground sewers were modeled as an exponentially decreasing function that ranged from $400 to $170 per linear foot (Figure 5). This range represents reported construction costs for underground sewer main construction (iron pipes) in Sacramento with a diameter of 4 to 24 inches at a depth of less than 10 feet (Huynh 2011). Additional costs for constructing pipe junctions, manholes, surface pavements, and landscaping were ignored. Similar ancillary costs would be required for all structural measures. Thus, total costs may be underestimated but the relative relationship between approaches is consistent. Moreover, including such ancillary costs could introduce more uncertainty than clarity. Figure 5 illustrates the decrease in unit costs of stormwater sewer construction across the urban region.

Figure 5: Unit costs of stormwater sewer construction as a function of distance from dense city center (Adapted from Huynh 2011)



For other actions, the analysis used estimates from literature for construction costs of channels, large-scale infiltration, local retention ponds (representing LID), and sewers. Construction costs for surface channels used estimates for grass covered channels with concrete paving (Metro Vancouver 1999; Foraste et al. 2011). Construction costs for large-scale infiltration basins were based on values for the Los Angeles metropolitan area (LADWP 2010), while construction costs for local retention basins were adapted (adjusted for inflation) from sources cited by the U.S. Environmental Protection Agency (SWRPC 1991; EPA 2008) and other research (Erickson 2009).

4.3 Treatment and maintenance costs

Stormwater treatment costs were incorporated as a mandate for treating runoff from sewers and channels. To treat runoff, cities must build treatment plants with enough peak flow capacity to prevent discharges during large storms. Costs for treatment capacity can be estimated as a unit charge per volume of water or as an annualized cost based on treatment plant operations. The analysis used the second approach. Treatment plant construction costs were estimated to be $1 million per 1.8e-4 ac-ft/sec, based on data for water treatment and reclamation plans in Los Angeles (LA Sewers 2013).

The sensitivity analysis incorporated increasingly stringent treatment requirements, ranging from zero to twenty percent of total stormwater runoff. The base case used zero percent treatment requirements, which reflects stormwater management in many regions.

Maintenance costs were estimated based on existing literature. Annual maintenance costs for sewers and channels were 3% of unit costs of construction (Wiegand et al. 1986; SWRPC 1991). Annual maintenance costs for large-scale infiltration basins were estimated as 1%, which was adapted from literature (Livingston et al. 1997). LID maintenance costs were modeled as 15% of construction costs (Wiegand et al. 1986; SWRPC 1991; Erickson 2009). All annual maintenance costs were assessed based on a present value estimation for 20 years (Collier & Ledbetter 1988).

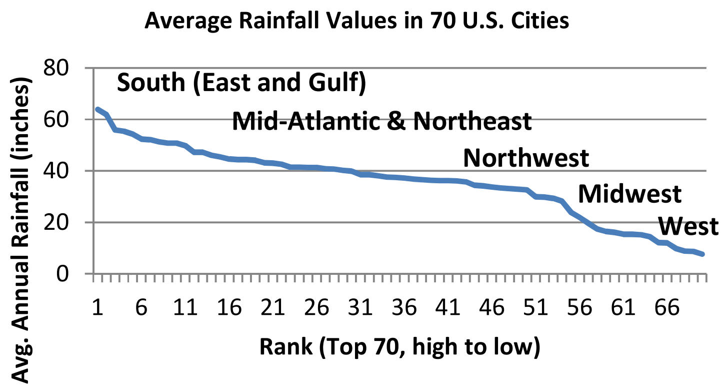
4.4 Environmental parameters: Infiltration and rainfall

Cites are regions of built infrastructure that influence many environmental processes, but they still exist within ecosystems. For stormwater management, two important characteristics are rainfall patterns and soil properties. Among U.S. cities, average rainfall values vary between 8 inches per year (Reno, NV) and 63 inches per year (Mobile, AL), as shown in Figure 6 (NOAA 2001). Infiltration rates vary based on soil type, including combinations of clay, loam, silt, and sand (Akan 2003).

The base case analysis used values typical for the Sacramento region. The sensitivity analysis varied these parameters to reflect cities in different environments, with the design storm (85^{th} percentile) rainfall ranging from 0.1 to 0.5 in/hr, and soil infiltration rates ranging from 0.06 to 1.0 in/hr. In theory, wet-weather cities with low infiltration rates require more stormwater infrastructure, while arid cities with high soil infiltration rates need less. Figure 6 shows both the distribution of average rainfall values in U.S. cities and the approximate steady-state infiltration rates for different soil types.

For structural measures that promote infiltration, parameters were based on literature. Large-scale capture basins are often located in fracture zones with higher recharge rates, estimated to be 4 inches/hour (Cutter et al. 2008). Rates of infiltration in LID vary widely, but were estimated as 3 inches/hour for steady-state infiltration in a retention pond (Alizadehtazi 2012).

Figure 6: Average rainfall (left) and variable infiltration rates (right) for U.S. cities



Source: (NOAA 2001)

Soil Type	Approximate Steady-State Infiltration Rate (in/hr)
Sand	> 1.0
Sand-Loam	0.85
Loam	0.5
Silt-loam	0.26
Silt-Clay	0.04
Clay	0.02

Source: Akan (2003), from Rawls et al (1983)

4.5 Imperviousness and Land Cover

Impervious surfaces, including roads, sidewalks, and buildings, inhibit infiltration. The percentage of impervious surfaces is higher in urban areas and an important consideration for stormwater management (Schueler 1994). Linear, exponential, and logarithmic relationships have been used to describe the relationship between imperviousness and common urban metrics, including population, housing, and distance from city center (Stankowski 1972; Graham et al. 1974; Gluck & McCuen 1975). Many studies have estimated how impervious surfaces vary with land use classification (Brabec et al. 2002). Urban ecology research provides a different framework for characterizing imperviousness in cities using land cover instead of land use classifications (Cadenasso et al. 2007). Cities have diverse collections of both pervious surfaces (lawns, gardens, and vacant lots) and impervious surfaces (roofs, roads, and sidewalks). Moreover, surfaces typically included in one category can be altered through design to fall into another. Green roofs, for example, can help impervious roof surfaces retain water. Incorporating detailed land cover characteristics can improve stormwater modeling.

In the analysis, imperviousness was estimated as a function of land value along the urban gradient from the downtown to the city outskirts (

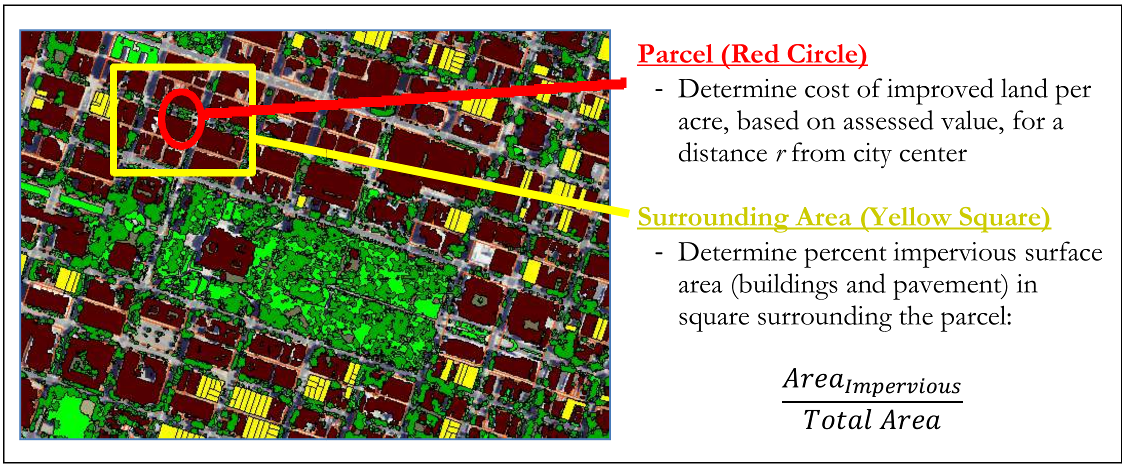
Figure 4). For each parcel in the base case, the percent of impervious land was estimated in the surrounding area using an existing land cover data set for the Sacramento region, as illustrated in Figure 7 (Cadenasso 2013). A Geographic Information System (GIS) layer delineated polygons for: pervious areas with grass, trees & shrubs, and bare dirt; buildings and pavement (roads and sidewalks), and water bodies. To determine the percent of impervious surfaces surrounding a property, I used the GIS layer to calculate: 1) the percentage of pervious land surrounding each point in the gradient using the *Geometry* tool in ArcGIS (ESRI 2012), and 2) the total area for each of the six land cover types in the square by summing the areas of the individual polygons.

The analysis indicated a linear, downward-sloping relationship between distance from city center (r) and percentage of impervious surface cover (I) across the metropolitan region ($R^2 = 0.58$):

$$I = -0.0143r + 0.824 \tag{25}$$

It provided a reasonable fit for the data and is corroborated by some prior research (Gluck & McCuen 1975; Brabec et al. 2002). The relationship, however, did show variability (Figure 8). The percent of impervious land was higher in more distant, newer suburbs than the closer, older suburbs. For future work, detailed urban land cover data can provide a new approach to better understand changes in land cover and pervious surfaces within cities.

Figure 7: Example section of land cover data set, with buildings (dark red), grass (light green), trees & shrubs (dark green), pavement (gray) and vacant lots (yellow). For a particular parcel (identified within the red circle), the percent of impervious surfaces (buildings and pavement) was calculated in the vicinity with an area of approximately 0.25-0.5 sq-miles (yellow square)



4.5.1 Linking distance, land value, and imperviousness

Distance from city center directly linked empirical values for imperviousness and property costs in the moderate-sized city. The linear relationship from Equation 25 identified the percent of impervious surfaces associated with particular distance from city center, which was correlated to property values through equations in Table 2.

For the sensitivity analysis of city size, empirical values of impervious surface cover from the base case city (moderate) must be correlated to property values in larger and smaller cities. As described above, downtown areas in more expensive cities were assumed to have higher land costs. The analysis also assumed that areas with higher property values had more imperviousness. This would not always be true if comparing for example, Los Angeles and New York City, but it is a reasonable estimate to compare New York City with Columbus, OH. I ranked property values from the three city sizes (small, moderate, and large). For land values in the moderate-size city, empirical values for impervious surface cover were known from the land cover data set. Values of impervious surface cover for properties in the small and large cities were calculated using a linear interpolation, as shown in Table 3.

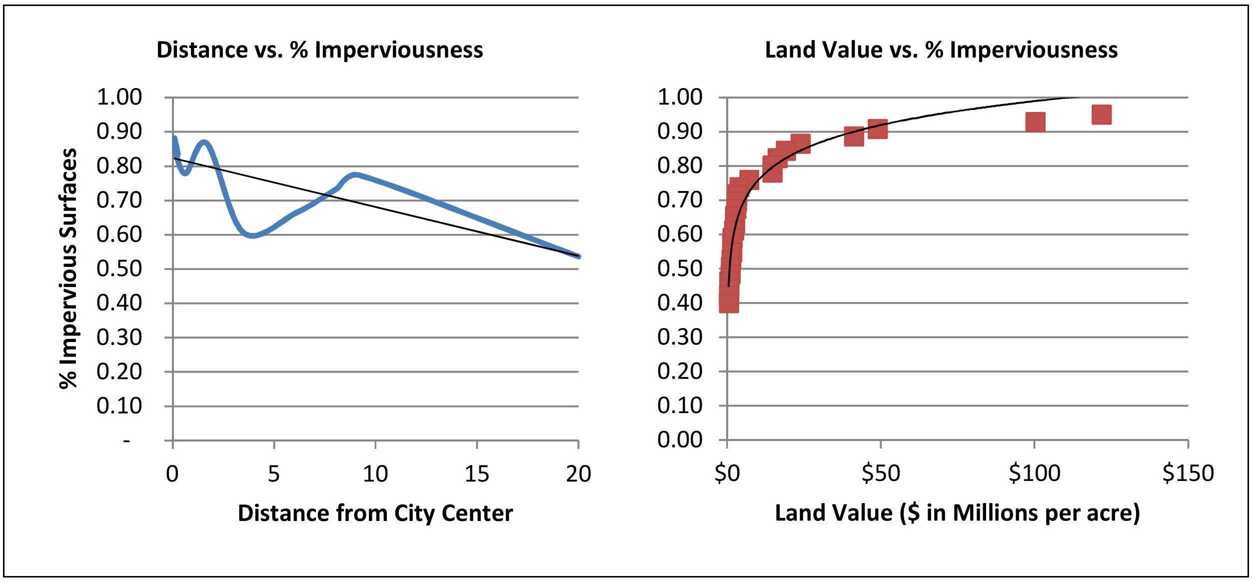
Table 3: Relating land values, city size, and impervious surface cover. Empirical values of impervious surface cover for the moderate-size city were calculated using land cover data. Interpolation provided values for cities of other sizes. (Sources: County of Sacramento, Cadenasso Lab (2013), Trimble Geospatial Imaging (2013))

Land Value per acre (millions)	City Size	Distance	% Impervious Surface Cover	
			Empirical	Interpolated
$121.79	Large	0.1	-	95%
$100.20	Large	0.1	-	93%
$41.16	Moderate	0.1	82%	89%
$23.78	Large	0.26	-	87%
$19.07	Small	0.1	-	84%

$16.31	Small	0.1	-	82%
$14.69	Large	0.63	-	80%
$14.62	Moderate	0.26	81%	78%
$7.11	Small	0.26	-	76%
$3.89	Large	3.5	-	74%
$3.22	Large	8.1	-	72%
$3.08	Moderate	0.63	80%	70%
$2.87	Large	6.1	-	67%
$2.48	Small	0.63	-	65%
$2.47	Moderate	1.7	75%	63%
$2.21	Large	9.2	-	61%
$1.62	Moderate	3.5	68%	59%
$1.52	Small	1.7	-	57%
$1.28	Moderate	6.1	57%	53%
$1.08	Large	1.7	-	51%
$1.06	Moderate	9.2	44%	48%
$0.65	Small	3.5	-	46%
$0.64	Small	8.1	-	44%
$0.53	Small	6.1	-	42%
$0.46	Small	9.2	-	40%

A logarithmic function (Equation 26), derived from the interpolation, describes the percent of impervious surface cover for a land parcel with a land value (improved) of $K(r)_L$ dollars/acre, as shown in Figure 8.

Figure 8: Percent of impervious surfaces in cities by distance from city center (left). Across the metropolitan region, land values correlate with distance from downtown (Section 3.1). Imperviousness was correlated with different land values by extrapolating from the empirical data for the Sacramento region and interpolating a logarithmic relationship between land value and impervious surface cover for many sizes of cities.



Without extrapolating from the base case, land cover at a distance of 1 mile in the large city would equal impervious land cover at the same location in the smaller city. The sensitivity analysis correlated surface cover with land values ranging from $50,000 to $40 million per acre, which represented all potential property values in the three regions.

$$I = (0.1006 * \ln(K(r)_L)) - 0.8636 \tag{26}$$

4.6 Stormwater removal requirements

Many methods exist for determining design storms and runoff removal capacity. The Soil Conservation Service (SCS) method divides the U.S. into regions with associated rainfall intensity and duration characteristics using historic records (NRCS 2010). In California, the State Water Resources Control Board mandates that metropolitan stormwater systems have sufficient capacity for runoff from a storm with an hourly precipitation in the 85th percentile of the annual distribution of rainfall events. The 85th percentile rainfall intensity in Sacramento (0.18 in/hr) was used in the base case. For the sensitivity analysis that analyzed rainfall in various cities, the 0.18 in/hr value was extrapolated to reflect a range based on the distribution of average annual rainfall in U.S. cities, as shown in Figure 6.

4.7 Model Implementation

I used the IBM ILOG CPLEX Studio Integrated Development Environment (IDE) to program the algorithm for optimization (IBM 2012). The IDE provides a Javascript® environment for implementing models with the ILOG CPLEX optimizer. The ILOG CPLEX Studio IDE was obtained through an academic license from IBM. Data was stored and analyzed in Microsoft Excel. I developed Python scripts using the open-source PyScripter IDE to control input and output procedures to the CPLEX optimization algorithm (Python Software Foundation 2001; Vlahos 2005).

5 Results

Results indicate how optimal stormwater allocations vary throughout the metropolitan region based on costs, regulations, and environmental characteristics. The results section describes major insights from the analysis, including how changes in city size, rainfall and infiltration, green infrastructure costs, treatment requirements, and existing infrastructure affect optimal allocations.

5.1 City size

Across metropolitan regions of different sizes, dominant stormwater strategies affect the unit costs and total costs of meeting removal requirements. Figure 9 illustrates how dominant stormwater measures vary with city size and distance from the dense region.

Landscape infiltration becomes more dominant as distance from the city center grows, but in medium and large cities it never dominates because land costs remain sufficiently high throughout the metropolitan region. In areas with moderate costs, channels remove the majority of runoff. As city size (and land costs) increase, storm sewers become more dominant. The range of city sizes shown in Figure 9 approximates small to medium-sized cities with populations that could span 200,000 to 800,000 residents. Larger and more expensive cities, equivalent to those with total populations in the millions, would have a larger percentage of area dominated by storm sewers.

Table 4: Description of analysis parameters for base case. The base case includes parameters for a city developing all new infrastructure.

Case	Description	Parameters	Value	Source
Base Case	Identify optimal allocations of stormwater management strategies throughout the metropolitan region. Incorporates values from literature for environmental parameters, land costs, treatment and maintenance requirements, and infrastructure costs.	***Environmental, Regulatory, and Economic Parameters***		
		Rainfall design rate	0.18 in/hr	NOAA (2001)
		Design storm duration	60 minutes	
		Soil infiltration rate	0.2 in/hr.	Akan (2003)
		Impervious surface cover	40-95%	Cadenasso Lab (2013)
		Land Values (per acre)	$.6-10 million	Sacramento County (2013)
		Infrastructure Parameters		
		Stormwater treatment costs	$200/ac-ft	Based on LADWP (2010)
		<u>Sewers</u>		
		Construction costs	$180-410/lin-ft	Huynh (2011)
		Annual maintenance costs	1% of const.	Metro Vancouver (1999)
		Sewer pipe width	2 ft.	n/a
		<u>Channels</u>		
		Construction (grassy channel)	$80/lin-ft	Metro Vancouver (1999)
		+ Concrete paving costs	$7/sq.ft	Foraste et al (2011)
		Annual maintenance costs	3% of const.	Based on SWRPC (1991)
		Channel width	4 ft.	n/a
		Channel depth	2 ft.	n/a
		<u>Green Infrastructure</u>		
		Construction costs (pond area)	$15/sq.ft	Based on Erickson (2009)
		Maintenance costs	15% of const.	Wiegland et al (1986), SWRPC (1991)
		Infiltration rate	4 in/hr	Alizadehtazi (2012)
		<u>Large-Scale Infiltration Basins</u>		
		Construction costs	$200/ac-ft	LADWP (2010)
		Maintenance costs	$.1/sq-ft	
		Infiltration rate	3 in/hr	Cutter et al (2008)
		<u>Flow Parameters</u>		
		Slope (pipes, channels)	0.001	
		Manning's n (concrete)	0.015	Akan (2003)

Table 5: Parameters included in sensitivity analysis cases. Only parameters that change from the base case are shown.

Case	Description	Parameter Changes from Base Case	Value	Source
City Size	How city density, simulated by variable land costs, affects optimal allocations. Underground sewers would be more viable in expensive cities due to land costs.	Land Values (per acre)	\$0.05-40 million	Adapted from Sacramento County (2013)
Rainfall and Infiltration	How weather (low to high rainfall) and soil type (low to high permeability) affect optimal allocations. Cities with high rainfall and poor permeability would have higher management costs than cities of low rainfall and high permeability.	Rainfall design rate Soil infiltration rate	0.1 to 0.5 in/hr 0.02 to 1.0 in/hr.	NOAA (2001) Akan (2003)
Costs of Green Infrastructure	How the cost of green infrastructure, also known as Low-Impact Development (LID) affect its adoption and allocation as a substitute for more traditional measures. Unit costs of green infrastructure are expected to decrease with wider adoption.	<u>Green Infrastructure</u> Construction costs (pond area) Maintenance costs	\$0.1 to \$15/sq.ft 10% of const.	Adapted from Brown & Scheuler (1997)
Treatment Requirements	How treatment requirements, modeled as higher percentage for treatment, affect optimal allocations. Treatment requirements may influence cities to consider new approaches.	Water treatment requirements Treatment plant annual costs, assessed for 20years	Treat 0 to 20% of total runoff \$1 million per 1.8e-4 ac-ft/s	EPA MS4 Permits LA Sewers (2013)
Maintenance Costs	How maintenance requirements, modeled through varied costs, affect optimal allocations. Maintenance costs may drive cities to consider new approaches.	Channel maintenance (/lin-ft) Sewer maintenance (/lin-ft)	\$1 to 5.5/lin-ft 1% to 8% of const. costs	n/a

Figure 9: Dominant stormwater strategies by city size and distance from city center. In small cities, channels and landscape infiltration dominate. As city size grows, the percentage of areas with storm sewer service increases. The region of analysis shows small- and medium-sized cities. In expensive cities, storm sewers become the dominant strategy.

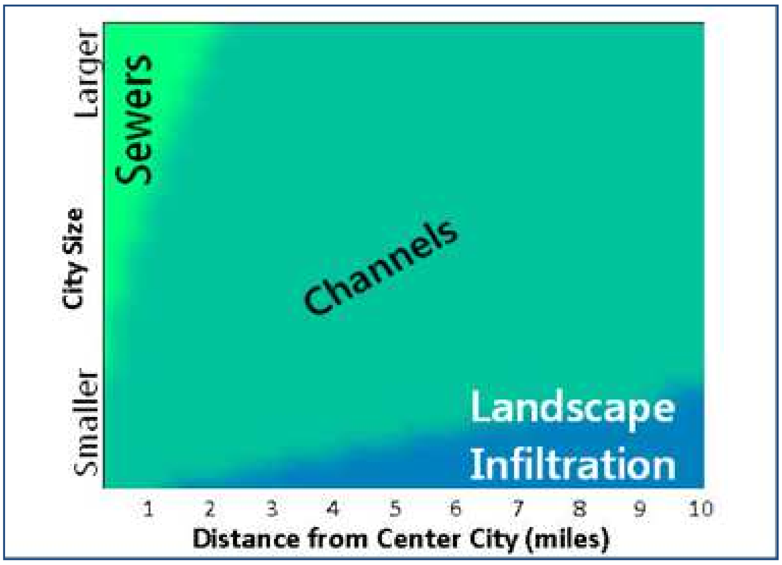


Figure 10 shows how unit costs and total costs change with increasing distance from city center. Near the downtown area, unit costs of removing stormwater are much higher than in suburban and ex-urban areas. Similarly, unit costs are higher in larger cities. Unit costs near downtown converge in large- and medium-sized cities, since sewer costs vary less than land costs. Total costs show the opposite relationship due to land area. Thus, while unit costs in the downtown are high, total costs increase because stormwater infrastructure must serve more land area in the ex-urban regions. Eventually, pervious surface cover will be high enough to enable more no-cost removal, but in the simulated regions, the percentage of impervious surface cover is still high in suburban areas.

Figure 10: Unit costs (left) and total costs (right) across metropolitan regions of different sizes. Unit costs are highest in the downtown area with high land costs, while total costs are largest in the outskirts because there is more land area and impervious surfaces still inhibit natural landscape infiltration.

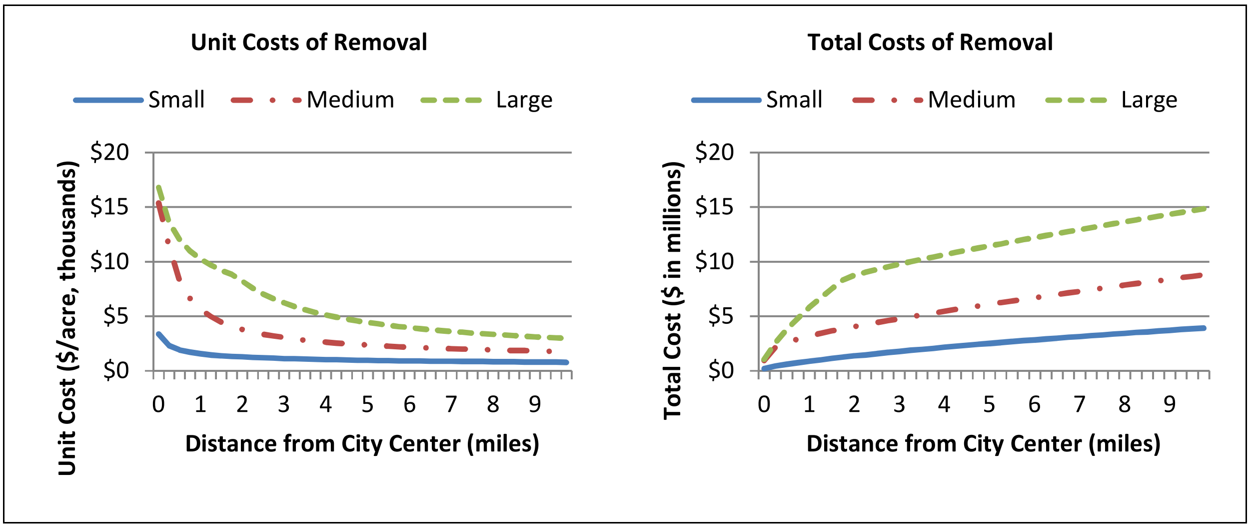
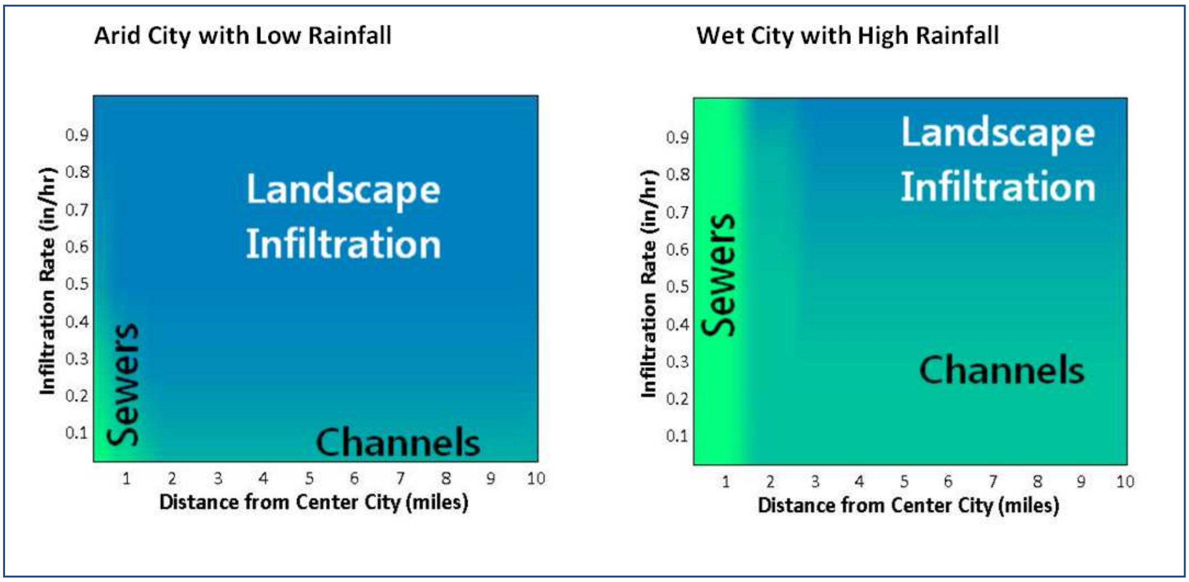


Figure 10 also illustrates the trade-off in density and land area for stormwater. Unit costs in dense areas are higher because infrastructure costs more to build. Sewers must go underground or channels must use expensive land. In the peripheral areas, unit costs are lower, but more area increases removal requirements.

5.2 Environmental parameters: Rainfall and infiltration

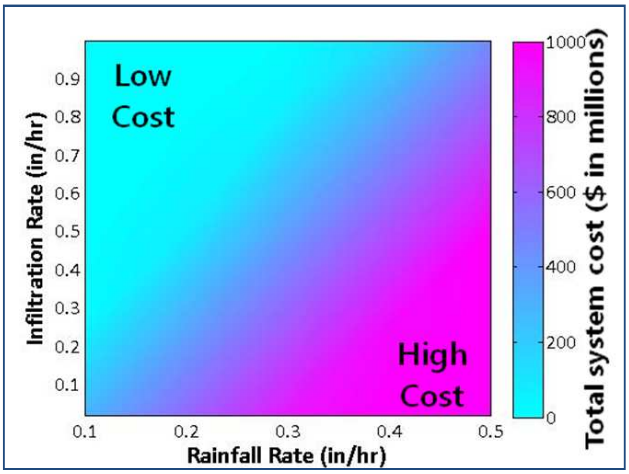
Stormwater management costs are closely related to regional environmental characteristics. Cities with lower rainfall and higher soil infiltration rates spend less on stormwater management infrastructure. Meanwhile, cities with high rainfall and impermeable soils need more infrastructure to meet removal targets. Figure 11 shows how allocations of stormwater measures change between arid and wet cities. Arid cities rely more on infiltration, while wet cities must build more sewers and channels.

Figure 11: Changes in dominant stormwater strategies for cities of low (left) and high (right) rainfall. In cities with less rainfall, landscape infiltration dominates across more of the metropolitan area, especially as soil infiltration rates increase. In wet weather cities with more rainfall, sewers and channels are more prominent.



Total costs increase with rainfall and decrease with soil infiltration rates, as shown in **Error! Not a valid bookmark self-reference.**. Applying results to a specific region could depend upon the unique characteristics of a region and associated design requirements. For instance, many arid cities with low rainfall experience storms of high intensity and short duration. The 85th percentile design storm target may be inadequate to protect from flooding, which would drive construction of more sewers and channels to manage large runoff volumes.

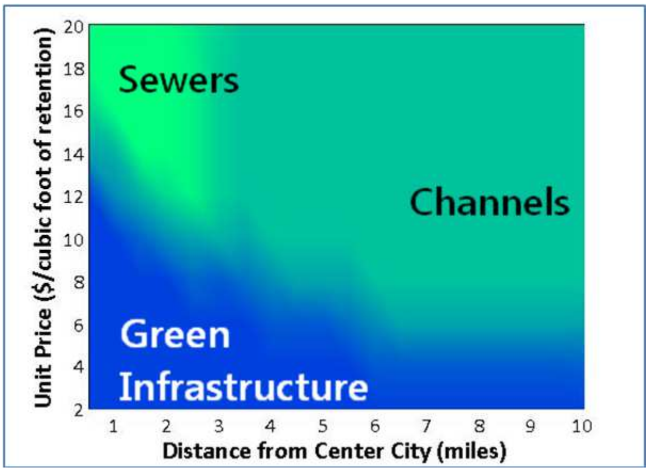
Figure 12: Stormwater removal costs across cities of varying rainfall and infiltration rates. Removal costs are larger in cities with higher rainfall and lower soil infiltration rates.



5.3 Alternative measures: LID and Infiltration Basins

LID provides an alternative to traditional conveyance approaches. The analysis tested how changes in cost for distributed retention basins affected the percentage of green infrastructure in the cost-effective mix of stormwater actions. As unit costs for constructing local retention basins decrease, LID becomes dominant in dense areas by replacing sewers. This only occurs, however, when land costs are not included with LID construction costs. Otherwise, it is not cost-effective without considering additional benefits or regulatory requirements. Many cities are using this strategy by building LID on public lands or incentivizing building owners to install LID in private developments. Although, green infrastructure enhances the ability of the landscape to manage runoff, it cannot remove the same volume of water as channels.

Figure 13: Dominant stormwater strategies across the metropolitan region with changing unit costs for construction of green infrastructure retention basins. As price decreases below $13/cubic foot, adoption increases in the city center as a substitute for sewers

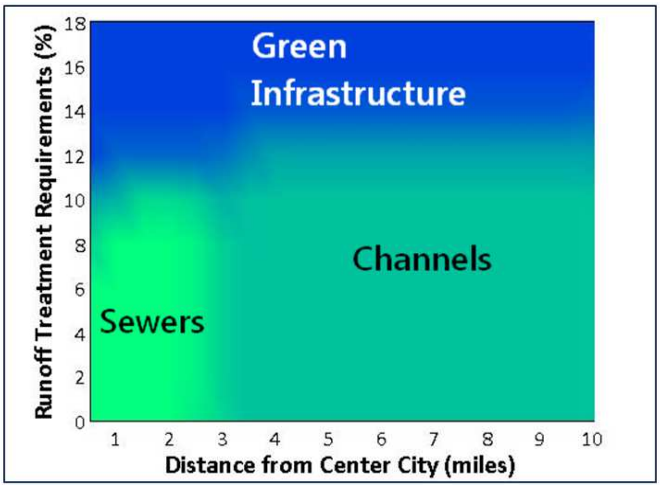


Large-scale basins for capturing and infiltrating stormwater runoff were not cost-effective. The value of such basins relates closely to aquifer recharge. In areas using such basins, benefits of stormwater capture are augmented by aquifer recharge to supply water and prevent saltwater intrusion.

5.4 Treatment requirements

As the percentage of runoff that needs treated increases beyond 10%, cities look instead to implement LID throughout the metropolitan region (Figure 14). Green infrastructure initially becomes cost-effective in dense areas, but as treatment requirements continue to increase, adoption becomes more widespread. EPA policies, which promote LID approaches, drive cities to undertake green infrastructure programs in lieu of significant upgrades for treating runoff.

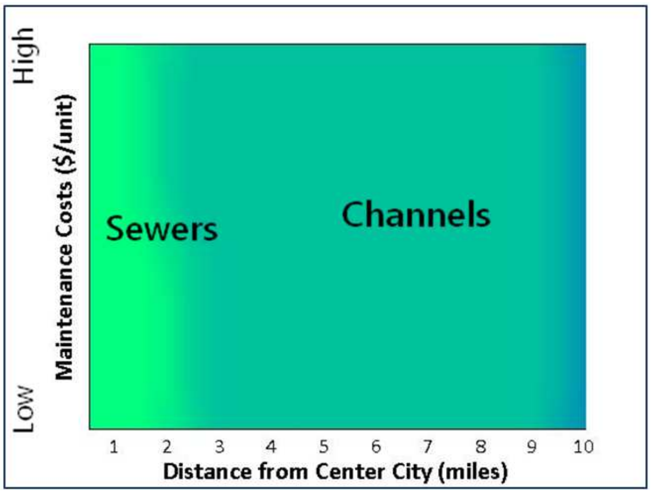
Figure 14: Dominant stormwater measures throughout the metropolitan region with changes in stormwater treatment requirements. As requirements increase, conveyance measures are replaced by green infrastructure.



5.5 Maintenance Requirements

Maintenance costs were assessed as a percentage of the construction costs (per linear foot) for both sewers and channels. This percentage for each was increased over a range of 1% to 10% of construction costs. Changes in maintenance costs, represented on the y-axis in Figure 15, had little effect on overall stormwater measures. Since both conveyance and infiltration actions have maintenance costs, it is less influential in promoting system change.

Figure 15: Optimal stormwater allocations across the metropolitan area with changes in maintenance costs. Maintenance costs were increased for both sewers and channels (y-axis)



6 Discussion

The analysis provided relevant points of discussion related to the relative value of each type of stormwater action in the metropolitan region, as well as the important factors influencing emerging trends.

<u>Sewers and Channels</u>: Both sewers and channels convey water quickly and efficiently, but land costs drive optimal allocations. Channels have the largest capacity, but the cost of land makes sewers more effective in downtown areas. Sewers in older cities, though, were built throughout more of the metropolitan region than is "cost-effective." Many older combined sewers were built in an era when disease was believed to spread through smells ("miasma theory"), which added an additional benefit to placing sewers underground (removing smells). Later, cities of the American West, which had more available land, built extensive surface channel networks to deal with "flashy" hydrology.

<u>Infiltration</u>: Infiltration is and old approach for managing stormwater, but emerging economic, regulatory, and technological trends are promoting its renewed use. New stormwater measures emphasize enhanced landscapes for distributed retention and infiltration (LID), as well as large-scale capture basins to promote stormwater retention. New designs must mesh existing conveyance systems (sewers and channels) with innovative infiltration measures. Different types of infiltration measures, though, provide different benefits. For instance, while landscape infiltration is often cost-effective, its capacity to manage runoff is limited. Infiltration infrastructure should be tailored to the climatic and geologic characteristics of a region.

<u>Hybrid Systems and Transition</u>: Promoters of new LID approaches emphasize the opportunity to reduce runoff from small and medium storms. Yet, urban flooding from large storms is a nuisance and danger. Managing runoff from large storms is still important. The real potential for innovative stormwater management is to integrate LID with conveyance that prevents floods from large storms. Yet, changing current systems to meet evolving regulatory requirements is challenging. Economies of scale favor continued use of existing systems, while current policies become entrenched within disciplines, organizations, laws, and policies. Both factors breed path dependence and affect management decisions and cost-effectiveness for stormwater systems.

6.1 Real-world comparisons

Results reflect past and current trends in urban stormwater management across many North American cities. For instance, cities everywhere use underground storm sewers in denser urban areas. Large cities such as New York, Atlanta, Chicago, and Seattle use underground conveyance to meet stormwater removal requirements over a large percentage of their metropolitan regions. Newer cities in western North American, many of which have lower population densities in core areas, use more surface conveyance measures than the older and denser cities of the east. This may relate both to the cost of land and the tendency for large cities in the early 20th century to combine stormwater and sanitary sewers.

Today, cities across the country are adopting green infrastructure as part of stormwater management plans. This is due in part to regulatory drivers. Model results showed, however, that decreasing unit costs for green infrastructure promote its use in cities to reduce treatment costs. Cities are redirecting existing funding lines and implementing LID on city-owned land to promote savings. For instance, in Syracuse, NY, which is touted as a leader for financing CSO improvements, funding lines combine improvements of traditional "gray" infrastructure with "greener" alternatives (Weaver 2013; Ondaga County Department of Water Environment Protection 2014). Many other cities mandate or incentivize on-site green infrastructure measures for private land development, which can forgo land acquisition costs. Moreover, LID is often developed on public lands near the city center, including parks and other city property. In Chicago, the city has a highly publicized effort to build green roofs on municipal buildings (Berkshire 2010).

Large-scale infiltration was not included as an optimal strategy, indicating its higher costs in comparison to LID and on-site infiltration. This reflects real-world practice. Large-scale infiltration basins are more cost-effective when considering aquifer recharge and saltwater intrusion. For instance, Los Angeles has maintained strategically-located basins in zones of high recharge for decades to mitigate groundwater overdraft. These areas use large-scale infiltration basins to treat, spread, and sink captured water. Large-scale infiltration basins have recognized aquifer recharge benefits, but research is still characterizing the benefits of distributed recharge through LID. Thus, while large-scale infiltration is widely adopted in some arid cities for its dual water supply and stormwater benefits, green infrastructure strategies primarily focus on only one urban water sector.

6.2 Limitations

As described throughout, the formulation and analysis includes simplifications and limitations. First, the geographic configuration of the model is overly-simplified. Cities have more environmental, economic, and social heterogeneity. Model results provide a framework for understanding the distribution of optimal measures that can later be applied with more detail. Second, the model only considered runoff volume from an 85th percentile design storm of sixty minutes duration. It ignored how inundation reduces soil infiltration capacity for long storms. Third, the model simplified construction costs of treatment plants. The costs of treatment plants are better assessed using both construction and operations costs. Capital costs can be defrayed through financing. Finally, the representation of LID in the model does not adequately address how different LID actions can accomplish different goals. For instance, green roofs absorb rainfall as well as improve energy performance, while swales and small infiltration zones reduce runoff accumulations. Adding more LID options would enhance the applicability of the modeling framework.

7 Conclusions

This chapter presented a metropolitan-scale decision model to identify cost-effective allocations of stormwater infrastructure that meet specified removal targets. Results describe how changes in cost-effective allocations are driven by an evolving mix of economic, environmental, technological, and regulatory factors. The results also reflect urban stormwater policies in many U.S. cities and provide insights for future systems development. The base case analysis showed that downtown areas are dominated by sewers, suburban areas use surface channels, and ex-urban regions in smaller cities benefit from landscape infiltration. The distribution of different stormwater actions in the region is driven by land values in cities, with underground sewers more cost-effective when property costs are high.

The sensitivity analysis revealed how changes in environmental, technological, and regulatory factors affect management. First, environmental factors, primarily average rainfall and soil infiltration, dictate the size of conveyance measures needed to meet design targets. Cities with higher average rainfall or lower soil infiltration rates need more structural measures. Second, green infrastructure becomes more widely adopted as its unit costs drop. Green infrastructure substitutes for sewer systems in downtown areas if cities forgo land acquisition costs by building in exiting right-of-ways. Third, stormwater treatment requirements drive the distribution of optimal allocations. Even small requirements (< 10%) for treating runoff motivate cities to reduce treatment costs using alternative measures. Finally, cities seek to maximize "no-cost" services of landscape infiltration in pervious areas, such as lawns and gardens. In the analysis, cities built just enough stormwater infrastructure to meet the gap between landscape infiltration and runoff removal targets. Promoting pervious surfaces in cities and increasing natural soil infiltration rates through technology can enhance stormwater practice.

The analysis raises several questions for management and policy. Since changes in unit cost changes drive adoption of green infrastructure, cities can stimulate cost reductions through both incentives and mandates. Its adoption will likely continue. Yet, little research characterizes potential pollution from widespread LID use. Soils break down contaminants, but long-term accumulation could foster a new era of urban groundwater and soil pollution, which resembles the potential for unforeseen effects described in urban environmental history literature. Thus, future research should incorporate potential contamination effects of widespread LID and incorporate it into planning. Additionally, research must develop better valuations of accessory benefits for LID, such as increased land values and health improvements. Finally, models are instructive tools to identify key drivers of evolution and change in complex urban systems.

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Chapter 4

Risk-Based Optimization of Stormwater Infrastructure in an Urban Region

However beautiful the strategy, you should occasionally look at the results.

- Winston Churchill

Abstract

Urban stormwater infrastructure must manage uncertainty in climatic events, transport of pollutants, and system operations. While urban flood risks initially motivated cities to build drainage infrastructure, today cities respond to regulatory requirements. Yet, cities must also consider new risks from larger and potentially more-frequent storms, making risk-based approaches again relevant for planning. This chapter presents an analysis to optimize cost-effective allocations of stormwater actions in a metropolitan region using a risk-based approach. It adapts the model presented in Chapter 3 to minimize the costs for system construction, maintenance, and treatment, along with expected flood damages and regulatory fines. Results indicate that the expected costs of flood damages motivate cities to build stormwater infrastructure, even at small estimates (1% of land values). Environmental regulations, simulated through fines for overflows, are an insignificant economic motivator. Coupling flood damages with environmental quality, or increasing fines for overflows, can spur cities to improve multi-objective goals for stormwater. The risk-based analysis reveals how U.S. stormwater management actions are driven by a mix of flood risks and regulatory requirements. Results help to explain how current state and federal stormwater permits influence emerging municipal stormwater trends.

1 Introduction

In the U.S., cities build stormwater infrastructure to mitigate flood risk and environmental degradation. The drainage capacity depends on geography, hydrology, design requirements, and regulations. Many cities estimate rainfall and runoff using procedures developed by the U.S. Soil Conservation Service, or SCS (1973). The SCS method uses hydrologic records to develop hyetographs of 24-hour design storms throughout the country. It estimates runoff using a unit hydrograph, which is based on timing, routing, land cover, and topography. Other cities use design storm targets (85th percentile) for stormwater planning. Metropolitan stormwater systems must also meet water quality regulations. Cities monitor and regulate water quality from stormwater sewer outflows, reporting data to state and federal regulatory agencies that may assess fines for contaminant releases above permitted levels.

U.S. metropolitan areas codify stormwater plans through municipal discharge permits in the National Pollutant Discharge Elimination Systems (NPDES). Cities with combined sewers and potential wet weather discharges of raw sewage are regulated through the Clean Water Act's Combined Sewer Overflow (CSO) Control Policy (EPA 1994). Alternatively, cities with separate systems acquire Municipal Separate Storm Sewer Systems (MS4) permits. Urban planners and private-sector developers use a variety of proprietary and commercial models to create stormwater plans and manage regulatory compliance.

Analyzing systems using risk-based approaches typically assesses benefits and costs of different actions, given possible events. The methods follow basic procedures to understand, characterize, and optimize outcomes:

> The present hierarchy of goals and objectives is scanned to isolate main problems. A hierarchy of goals and objectives is set up, and is edited to manageable proportions. An inventory of available resources is established. Alternative ways of meeting the objectives are hypothesized and then

> evaluated in terms of some common metric of costs and benefits, generally associated with the achievement of the objectives. Usually, some calculation is made of probabilities of different courses of action; the preferred course is the one that maximizes the net expectation (probability multiplied by utility) (Hall 1982 p. 190).

Risk-based flood prevention, including stormwater, must balance flood risks with costs of protective infrastructure by estimating: 1) likely rainfall events (Klemes 2000), and 2) flood damages (Grigg & Helweg 1975; USACE 1988). Optimizing outcomes to minimize damages or maximize benefits can evaluate cost-effective sizing of structural flood control measures (James 1967; Jacoby & Loucks 1972; Davis 1974). Probabilistic approaches based on likely rainfall events and corresponding runoff typically minimize expected damages (Davis et al. 1972; USACE 1996; Lund 2002; Zhu et al. 2007).

Risks in stormwater management result from many factors (Heaney et al. 1996). Hydrology, including the density, duration, and frequency of storms, drives risk. Probability distributions and Monte Carlo analysis can incorporate uncertainty of rainfall events and characterize runoff from likely storms (Guo & Urbonas 2002; Korving et al. 2003, 2009). Large, infrequent storms present significant management challenges. Urban floods from stormwater overflows can cause physical damages, which may be estimated using expected annual damage calculations (Lind 1967; USWRC 1983; Lund 2002). Treating stormwater runoff in older cities with combined sewers is problematic when large storms cause Combined Sewer Overflows (CSOs). Many use temporary storage to mitigate overflows, which requires uncertainty estimates for inflows and outflows in storage basins, as well as the sizing of pipes, basins, and storage tanks (Jacobs et al. 1993; Guo & Hughes 2001; Guo 2002; Guo & Urbonas 2002; Korving et al. 2003). The likelihood of CSOs can be approximated using common statistical distributions (Korving et al. 2002). Other operational decisions such as pumping policies also help to mitigate overflows (Piantadosi et al. 2008). Furthermore, aging sewer systems require maintenance. Reliability in sewer operation can affect scheduling for low-cost rehabilitation and upgrades (Jacobs et al. 1993; Korving et al. 2003, 2009). Finally, environmental effects such as stream and channel erosion add to anthropogenic sources of contamination and may be estimated using probabilities (Bledsoe & Watson 2001). Risk-based management of runoff quantity and quality can enhance multi-objective goals that use stormwater "as a resource" (Wong & Eadie 2000).

This chapter adapts the metropolitan stormwater planning model presented in Chapter 3 to identify optimal allocations of stormwater infrastructure using a risk-based planning framework. As cities recognize growing risks from climate, water scarcity, and other sources of uncertainty, risk planning considerations are becoming more widespread. For stormwater, urban flood risks from large and potentially more-frequent storms can drive cities to combine risk planning with traditional design targets for design and management. The analysis primarily seeks to understand how risk-based approaches for stormwater planning change the cost-effective mix of stormwater allocations across a metropolitan region. Specifically, the analysis integrates risk considerations into economically efficient planning using expected damages from flooding and pollution.

2 Model Formulation

The optimization used a mixed-integer programming formulation to minimize total costs of stormwater removal infrastructure (Z) in a metropolitan region based on costs for construction, treatment, and maintenance, as well as expected damages from flooding and regulatory fines. Decision variables (in bold below) determine the area devoted to physical infrastructure at a distance *r* from downtown for sewer pipes ($A_S(r)$), surface channels ($A_C(r)$), large-scale infiltration basins ($A_{MI}(r)$), and local retention basins representing LID ($A_{LID}(r)$).

Total system costs, *Z,* are the sum of costs for construction, C_N, treatment, C_T, and maintenance, C_M, as well as probability-weighted flood damages, X, and fines, F, which may occur following a rainfall event with a probability, *p*. The probability of rainfall is based on the likelihood of an event occurring on a particular day of the year given typical average daily rainfall values (see Section 3.2). The risk-based approach assesses costs based on the location in the metropolitan region (*r*), day of the year (*t*), and the probability of a rainfall event (*p*) with a depth of *D* on day *t*, such that:

$$Min\ Z = \int_0^R \Bigg(C_N\big(r, \boldsymbol{A_S(r)}, \boldsymbol{A_C(r)}, \boldsymbol{A_I(r)}\big) + \beta C_M\big(\boldsymbol{r}, \boldsymbol{A_S(r)}, \boldsymbol{A_C(r)}, \boldsymbol{A_I(r)}\big)$$
$$+ \sum_{t=1}^{D} \beta C_T\big(\boldsymbol{r}, \boldsymbol{t}, \boldsymbol{A_S(r)}, \boldsymbol{A_C(r)}, \boldsymbol{A_I(r)}\big) \tag{1}$$
$$+ \beta \int_0^P Pr(p,t)\,[X(r,t,p,\boldsymbol{A_S(r)}, \boldsymbol{A_C(r)}, \boldsymbol{A_I(r)}) + F(r,t,p,\boldsymbol{A_S(r)}, \boldsymbol{A_C(r)}, \boldsymbol{A_I(r)})]\Bigg) dr\, dp$$

Where: $r = Distance\ from\ downtown\ area$
$T \in \{Days\}$
$p = Probability\ of\ rainfall\ event\ with\ a\ depth\ of\ D$
$\beta = multiplier\ for\ annualized\ costs$

2.1 Construction Costs

The costs of construction, maintenance, and treatment include costs for sewers (C_S), surface channels (C_C), and infiltration (C_I), across the metropolitan area:

$$C\big(r, \boldsymbol{A_s(r)}, \boldsymbol{A_C(r)}, \boldsymbol{A_I(r)}\big) = C_S\big(r, \boldsymbol{A_s(r)}\big) + C_C\big(r, \boldsymbol{A_C(r)}\big) + C_I\big(r, \boldsymbol{A_I(r)}\big) \tag{2}$$

The unit costs associated with each type of action differ, as described in Chapter 3. For instance, while sewers have construction, treatment, and maintenance costs, surface channels have additional costs for acquiring land. Moreover, different types of infiltration have differing costs, including large-scale basins, LID/green infrastructure (distributed) measures, and on-site infiltration in landscapes. Large-scale basins and LID have construction costs, but no infiltration measures have treatment costs:

$$\textit{Construction:}\quad C_N(r, \boldsymbol{A_s(r)}, \boldsymbol{A_C(r)}, \boldsymbol{A_I(r)}) = C_{N_S}(r, \boldsymbol{A_s(r)}) + C_{N_C}(r, \boldsymbol{A_C(r)}) + C_{N_I}(r, \boldsymbol{A_I(r)}) \tag{3}$$

$$\textit{Maintenance:}\quad C_M(r, \boldsymbol{A_s(r)}, \boldsymbol{A_C(r)}, \boldsymbol{A_I(r)}) = C_{M_S}(r, \boldsymbol{A_s(r)}) + C_{M_C}(r, \boldsymbol{A_C(r)}) + C_{M_I}(r, \boldsymbol{A_I(r)}) \tag{4}$$

$$\textit{Treatment:}\quad C_T(r, \boldsymbol{A_s(r)}, \boldsymbol{A_C(r)}) = C_{T_S}(r, \boldsymbol{A_s(r)}) + C_{T_C}(r, \boldsymbol{A_C(r)}) \tag{5}$$

$$\textit{Land:}\quad C_L\big(r, \boldsymbol{A_C(r)}, \boldsymbol{A_I(r)}\big) = C_{L_C}(r, \boldsymbol{A_C(r)}) + C_{L_I}\big(r, \boldsymbol{A_I(r)}\big) \tag{6}$$

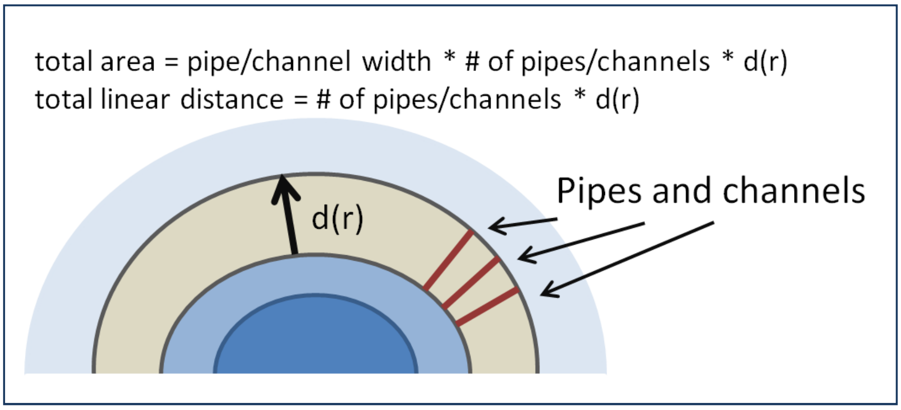
Construction costs for each possible stormwater action are based on unit costs using the same procedures as in Chapter 3. Unit costs of sewers and channels $\big(K_{N_S}(r)\ and\ K_{N_C}(r)\big)$ are assessed per linear foot. The model selects the areas allocated to sewers and channels, divides by the specified width of pipes and channels to calculate the number conveyance structures in each region, and then multiplies these values by the linear distance $\big(d(r)\big)$ to calculate the total length of each action.

$$\textit{Sewer Construction:}\quad C_{N_S}(r, A_S(r)) = \left(\frac{d(r) * \boldsymbol{A_S(r)}}{W_S(r)}\right)\big(K_{N_S}(r)\big) \tag{7}$$

$$\textit{Channel Construction:}\quad C_{N_C}(r, A_C(r)) = \left(\frac{d(r) * \boldsymbol{A_C}(r)}{W_C(r)}\right)\big(K_{N_C}(r)\big) + \big(\boldsymbol{A_C}(r)\big)\big(K_L(r)\big) \tag{8}$$

The formulation assumes that pipes and channels are dispersed throughout the region. Figure 1 illustrates this procedure.

Figure 1: Method for converting decision variables of total area for sewers and channels in each region to a linear distance, which is used to calculate costs. The total area for conveyance in a region through sewers and channels is assumed to be dispersed throughout the region and span its length (*d(r)*). Dividing the area of pipes and channels by the assumed widths gives the number of pipes and channels in a region.



Infiltration in large-scale basins and LID has construction costs. Large-scale infiltration also includes costs for acquiring land, while LID measures only include construction costs, as the model assumes that cities forgo land costs by implementing LID measures in existing urban landscapes on public lands or through private property mandates. This matches emerging metropolitan management practices.

Infiltration Constr.: $$C_{N_I}\big(r, \boldsymbol{A_{MI}(r)}, \boldsymbol{A_{LID}(r)}\big) = C_{N_{MI}}\big(r, \boldsymbol{A_{MI}(r)}, \boldsymbol{A_{LID}(r)}\big) + C_{N_{LID}}\big(r, \boldsymbol{A_{MI}(r)}, \boldsymbol{A_{LID}(r)}\big) \quad (9)$$

MI Construction: $$C_{N_{MI}}\big(r, \boldsymbol{A_{MI}(r)}\big) = \boldsymbol{A_{MI}(r)} * \big(K_{N_{MI}}(r) + K_L(r)\big) \quad (10)$$

LID Construction: $$C_{N_{LID}}\big(r, \boldsymbol{A_{LID}(r)}\big) = \boldsymbol{A_{LID}(r)} * \big(K_{N_{MI}}(r)\big) \quad (11)$$

The model assesses costs for maintenance and treatment in sewers, channels, managed infiltration, and LID measures, as well as expected damages and fines, based on the present value annualized over 20 years. A multiplication factor calculates the total value in present-day dollars of annual costs, $\boldsymbol{C_{OM}}$, over a period of *Y* years, based on an assumed inflation rate *b* and an interest rate *i* (Collier & Ledbetter 1988):

Present Value of Maintenance Costs: $$PV = C_{OM} * \beta(Y) = C_{OM} * \left(\frac{\left(\frac{1+b}{1+i}\right)^Y - 1}{r - i} \right) \quad (12)$$

2.2 Maintenance Costs

Total maintenance for sewers and channels is the product of the total capacity and the unit cost of maintenance for each measure ($K_{M_S}(r)$ and $K_{M_C}(r)$), which are assumed to be a percentage of construction costs, and a multiplication factor, β, to annualize 20 years of maintenance costs.

$$C_{M_S}(r, \boldsymbol{A_S(r)}) = \left(\frac{d(r) * \boldsymbol{A_S(r)}}{W_S(r)}\right)\left(K_{M_S}(r)\right) * \beta(Y) \tag{13}$$

Sewer Maintenance Costs:

$$C_{M_C}(r, \boldsymbol{A_C(r)}) = \left(\frac{d(r) * \boldsymbol{A_C(r)}}{W_C(r)}\right)\left(K_{M_C}(r)\right) * \beta(Y) \tag{14}$$

Channel Maintenance Costs:

For infiltration, only large-scale infiltration basins and LID sites have maintenance costs:

Infiltration Maintenance:

$$C_{M_I}(r, \boldsymbol{A_{MI}(r)}, \boldsymbol{A_{LID}(r)}) = C_{M_{MI}}(r, \boldsymbol{A_{MI}(r)}) + C_{M_{LID}}(r, \boldsymbol{A_{LID}(r)}) \tag{15}$$

MI Maintenance:

$$C_{M_{MI}}(r, \boldsymbol{A_{MI}(r)}) = \boldsymbol{A_{MI}(r)} * K_{M_{MI}}(r) * \beta(Y) \tag{16}$$

LID Maintenance:

$$C_{M_{LID}}(r, \boldsymbol{A_{LID}(r)}) = \boldsymbol{A_{LID}(r)} * K_{M_{LID}}(r) * \beta(Y) \tag{17}$$

2.3 Treatment Costs

The model assessed treatment costs for sewers, $C_{T_S}(r)$, and channels, $C_{T_C}(r)$, by multiplying the total design flow capacity of each conveyance action and the annual unit cost of building treatment plant facilities to the flow specification. Annualized total costs for water treatment operations are calculated similar to the procedure for maintenance costs.

Treatment Costs for Sewers:

$$C_{T_S}(r, \boldsymbol{A_S(r)}) = Q_S(r, \boldsymbol{A_S(r)}) * K_T * \beta(Y) \tag{18}$$

Treatment Costs for Channels:

$$C_{T_C}(r, \boldsymbol{A_C(r)}) = Q_C(r, \boldsymbol{A_C(r)}) * K_T * \beta(Y) \tag{19}$$

2.4 Removal Capacity

The model calculates total removal capacity, $\boldsymbol{Q_T}$, using standard equations for flow and infiltration similar to Chapter 3, where sewers, $Q_S(r, \boldsymbol{A_S(r)})$, channels, $Q_C(r, \boldsymbol{A_C(r)})$, and infiltration, $Q_I(r, \boldsymbol{A_{MI}(r)}, \boldsymbol{A_{LID}(r)})$ all provide removal capacity based on the allocated area. The total removal capacity, , is equal to the sum of removal capacities for each action. Equations 20-24 list the flow calculations.

Total Removal:

$$Q_T = \int_0^R \left(Q_S(r, \boldsymbol{A_S(r)}) + Q_C(r, \boldsymbol{A_C(r)}) + Q_I(r, \boldsymbol{A_{MI}(r)}, \boldsymbol{A_{LID}(r)})\right) dr \tag{20}$$

Removal Per Region:

$$Q_S(r, \boldsymbol{A_S(r)}) + Q_C(r, \boldsymbol{A_C(r)}) + Q_I(r) \geq Q_{design}(r) \tag{21}$$

Sewer:

$$Q_S(r, \boldsymbol{A_S(r)}) = \left(\frac{.463}{n}\right)\left(\frac{H}{P}\right)^{8/3} (S(r))^{1/2} \tag{22}$$

Channel:

$$Q_C(r, \boldsymbol{A_C(r)}) = \left(\frac{1.49}{n}\right) A_{CS}(R)^{2/3} (S(r))^{1/2} \tag{23}$$

Infiltration:

$$Q_I(r, \boldsymbol{A_{MI}(r)}, \boldsymbol{A_{LID}(r)}) = i_{MI}\, \boldsymbol{A_{MI}(r)} + i_{LID}\, \boldsymbol{A_{LID}(r)} + i_L \left(\boldsymbol{A_{LI}(r)} * \left(1 - I(K_L(r))\right)\right) \tag{24}$$

2.5 Damages and Fines

Damages and fines accrue when the volume of stormwater runoff exceeds the designed capacity of the system. The volume of stormwater a city must manage is related to precipitation and land area. The total volume of runoff in a region $\left(V\left(r,t,p,\boldsymbol{A_S}(\boldsymbol{r}),\boldsymbol{A_C}(\boldsymbol{r}),\boldsymbol{A_I}(\boldsymbol{r})\right)\right)$ associated with a probability-weighted storm is the product of rainfall depth (D) of a storm and the area of the region $(A(r))$, divided by the storm duration:

$$V\left(r,t,p,\boldsymbol{A_S}(\boldsymbol{r}),\boldsymbol{A_C}(\boldsymbol{r}),\boldsymbol{A_I}(\boldsymbol{r})\right) = \frac{D(r,t,p) * A(r)}{t_d} \tag{25}$$

When runoff volume exceeds design capacity, flood damages $\left(X\left(r,t,p,\boldsymbol{A_S}(\boldsymbol{r}),\boldsymbol{A_C}(\boldsymbol{r}),\boldsymbol{A_I}(\boldsymbol{r})\right)\right)$ accrue as a percentage (r_D) of property values:

$$X(r,m,p) = \begin{cases} r_D * K_L(r) * A(r) * Pr(p,t) & if\ V\left(r,t,p,\boldsymbol{A_S}(\boldsymbol{r}),\boldsymbol{A_C}(\boldsymbol{r}),\boldsymbol{A_I}(\boldsymbol{r})\right) \geq Q(r) \\ \$0 & if\ V\left(r,t,p,\boldsymbol{A_S}(\boldsymbol{r}),\boldsymbol{A_C}(\boldsymbol{r}),\boldsymbol{A_I}(\boldsymbol{r})\right) \leq Q(r) \end{cases} \tag{26}$$

Similarly, fines for contaminated water overflows ($10,000 per daily offense) occur when runoff exceeds design capacity:

$$F\left(r,t,p,\boldsymbol{A_S}(\boldsymbol{r}),\boldsymbol{A_C}(\boldsymbol{r}),\boldsymbol{A_I}(\boldsymbol{r})\right) = \begin{cases} \$10{,}000 & if\ V\left(r,t,p,\boldsymbol{A_S}(\boldsymbol{r}),\boldsymbol{A_C}(\boldsymbol{r}),\boldsymbol{A_I}(\boldsymbol{r})\right) \geq Q(r) \\ \$0 & if\ V\left(r,t,p,\boldsymbol{A_S}(\boldsymbol{r}),\boldsymbol{A_C}(\boldsymbol{r}),\boldsymbol{A_I}(\boldsymbol{r})\right) \leq Q(r) \end{cases} \tag{27}$$

The present values (over a 20-year period) of damages $(X(r)_A)$ and fines $(D(r)_A)$ are calculated using the multiplier for annualizing long-term costs (from Equation 12):

Present Value of Annualized Damages:

$$X\left(r,\boldsymbol{A_S}(\boldsymbol{r}),\boldsymbol{A_C}(\boldsymbol{r}),\boldsymbol{A_I}(\boldsymbol{r})\right)_A = \sum_{t=1}^{T} \beta \int_0^P X\left(r,t,p,\boldsymbol{A_S}(\boldsymbol{r}),\boldsymbol{A_C}(\boldsymbol{r}),\boldsymbol{A_I}(\boldsymbol{r})\right) dp \tag{28}$$

Present Value of Annualized Fines:

$$F\left(r,\boldsymbol{A_S}(\boldsymbol{r}),\boldsymbol{A_C}(\boldsymbol{r}),\boldsymbol{A_I}(\boldsymbol{r})\right)_A = \sum_{t=1}^{T} \beta \int_0^P F\left(r,t,p,\boldsymbol{A_S}(\boldsymbol{r}),\boldsymbol{A_C}(\boldsymbol{r}),\boldsymbol{A_I}(\boldsymbol{r})\right) dp \tag{29}$$

Finally, non-negativity constraints are applied to all decision variables, while the combined area for infiltration, surface conveyance, and other land (buildings, roads, etc) in a region cannot exceed the total area of that region:

$$A_{total}(r) = \boldsymbol{A_C}(\boldsymbol{r}) + \boldsymbol{A_{MI}}(\boldsymbol{r}) + \boldsymbol{A_{LID}}(\boldsymbol{r}) + \boldsymbol{A_{LI}}(\boldsymbol{r}) + \boldsymbol{A_O}(\boldsymbol{r}) \tag{30}$$

Table 1 gives the complete list of variables included in the model.

Table 1: List of variables included in the model

Variable	Description	Symbol
Primary decision variables: Area		
Sewers Area	Total area (underground) for sewer conveyance in a region of the metropolitan area. Used to calculate total pipe length	$A_S(r)$

Channels Area	Total area for surface conveyance in channels in a region of the metropolitan area. Used to calculate total channel length	$A_C(r)$
Managed Infiltration Area	Total area for large-scale managed infiltration basins in a region of the metropolitan area	$A_{MI}(r)$
Low-Impact Development (LID) Area	Total area for LID/green infrastructure measures, modeled as retention ponds, in a region of the metropolitan area. LID strategies would assume to be dispersed throughout the landscape	$A_{LID}(r)$
Landscape Infiltration Area	Remaining portion of landscape in a region of the metropolitan area that has pervious surfaces to provide removal through infiltration	$A_{LI}(r)$
Other Land Area	Land not included in stormwater measures. Includes impervious areas in the urban landscape	$A_O(r)$
Calculated (secondary) decision variables based on area: Removal (Flow) Capacity and Costs		
Flow variables		
Sewers	Total flow capacity for stormwater removal through sewer conveyance	$Q_S(r, A_S(r))$
Channels	Total flow capacity for stormwater removal through channel conveyance	$Q_C(r, A_C(r))$
Managed Infiltration sites	Total removal capacity from managed infiltration	$Q_I(r, A_{MI}(r))$
Low-Impact Development (LID) sites	Total removal capacity from LID measures (retention ponds)	$Q_I(r, A_{LID}(r))$
Landscape Infiltration	Total removal capacity in the landscape. This removal is considered free, but constrained by environmental limits and urban structure.	$Q_I(r, A_{MI}(r), A_{LID}(r))$
Costs		
Total System Costs	Total costs for removal	Z
Total Costs of Sewers by region	Total costs for sewer measures, including construction, treatment, and maintenance, in a region of the metropolitan area	$C_S(r, A(r)_S)$
Construction Costs of Sewers	Costs for sewer construction	$C_{N_S}(r, A(r)_S)$
Treatment Costs of Sewers	Costs for treating stormwater conveyed through sewers	$C_{T_S}(r, A(r)_S)$
Maintenance Costs of Sewers	Costs for maintaining sewers, calculated for 20-year annualized costs	$C_{M_S}(r, A(r)_S)$
Total Costs of Channels by region	Total costs for channel measures, including construction, treatment, maintenance, and land costs, in a region of the metropolitan area	$C_C(r, A(r)_C)$
Construction Costs of Channels	Costs for channel construction	$C_{N_C}(r, A(r)_C)$
Treatment Costs of Channels	Costs for treating stormwater conveyed through channels	$C_{T_C}(r, A(r)_C)$
Maintenance Costs of Channels	Costs for maintaining channels, calculated for 20-year annualized costs	$C_{M_C}(r, A(r)_C)$
Land Costs of Channels	Land acquisition costs for surface channels, based on land values in each region	$C_{L_C}(r, A_C(r)$
Total Costs for Infiltration	Total costs for all infiltration measures, including Low-Impact Development and large-scale, managed infiltration basins, in a region of the metropolitan area.	$C_I(r, A(r)_{MI,}(A(r)_{LID})$

Managed Infiltration construction	Costs for construction of large-scale infiltration basins, including infrastructure and land costs	$C_{MI}(r, A(r)_{MI})$
Managed Infiltration maintenance	Costs for maintaining infiltration basins, calculated for 20-year annualized costs	$C_{N_{MI}}(r, A(r)_{MI})$
Construction Costs of LID	Costs for construction of LID measures (retention ponds)	$C_{N_{LID}}(r, A(r)_{LID})$
Maintenance Costs of LID	Costs for maintaining LID measures, calculated for 20-year annualized costs	$C_{M_{LID}}(r, A(r)_{LID})$
Parameters		
Radius	Distance of a region from the downtown center	r
Infiltration rates		
Infiltration rate in managed basins	Infiltration rate in large-scale basins, which are typically sites in areas of high recharge rates	i_{MI}
Infiltration rate for landscapes	Based on soil characteristics. This infiltration rate is applied to all pervious areas that are not LID or large-scale basin sites	i_L
Infiltration rate in LID sites	Infiltration rate at LID sites, which are typically engineered to increase removal capacity	i_{LID}
Hydraulic parameters		
Sewer pipe diameter	Diameter of sewer pipes, assumed to be constant throughout regions	H
Manning's n	Roughness coefficient for channel and pipe flow calculations using Manning's equations	n
Slope	Slope for calculated flow in pipes and channels	$S(r)$
Hydraulic radius	Equation to the cross-sectional area of flow divided by the wetted perimeter. Used in equation for channel flow	R
Channel cross-sectional area	Cross-sectional area of channels, used in calculating channel flow	A_{CS}
Diameter (length) of a region	Linear distance (length) of the semi-circular region in the metropolitan area. Used to calculate total length of sewers and channels	$d(r)$
Economic parameters		
Inflation rate	Assumed rate of inflation used to calculate 20-year annualized costs	b
Interest rate	Assumed interest rate used to calculate 20-year annualized costs	i
Infrastructure lifespan	Time period for calculating present value of annual costs	n
Annualized cost multiplier	Calculated value, based on interest rate, rate of inflation, and infrastructure lifespan	β
Unit Costs		
Land	Land costs, per acre, including the value of both land area and building improvements	$K_L(r)$
Sewer construction	Unit cost for building sewers, per linear foot.	$K_{N_S}(r)$
Channel construction	Unit cost for building channels, per linear foot.	$K_{N_C}(r)$
Managed infiltration basin construction	Unit cost for building managed infiltration basins, per acre-foot of flow capacity	$K_{N_{MI}}(r)$
LID construction	Unit cost for building LID sites, modeled as retention ponds, per square foot of area for a pond with a maximum depth of 5 feet	$K_{N_{MI}}(r)$
Treatment	Unit cost for building water treatment plants,	K_T

	based on unit costs for design flow capacities.	
Sewer maintenance	Unit cost for maintenance of sewers. Present value costs of annual maintenance are calculated over 20 years.	$K_{M_S}(r)$
Channel maintenance	Unit cost for maintenance of channels. Present value costs of annual maintenance are calculated over 20 years.	$K_{M_C}(r)$
Managed infiltration maintenance	Unit cost for maintenance of managed infiltration basins. Present value costs of annual maintenance are calculated over 20 years.	$K_{M_{MI}}(r)$
LID maintenance	Unit cost for maintenance of LID sites. Present value costs of annual maintenance are calculated over 20 years.	$K_{M_{LID}}(r)$
Damages and Fines		
Damage rate	Damages by flooding, as a rate of property values	r_D
Flood damages	Annualized flood damages in a region	$X\left(r, A_S(r), A_C(r), A_I(r)\right)_A$
Fines for overflows	Annualized overflow penalties in a region	$F\left(r, A_S(r), A_C(r), A_I(r)\right)_A$

3 Parameters and Implementation

The risk-based model used the same structure for the metropolitan region as described in Chapter 3. Parameters for land values, infiltration rates, imperviousness, and costs of construction and maintenance were all similar (see Table 4 in Chapter 3). Sections 3.1-3.2 describe the parameters that changed in the risk-based model: assessed fines and damages and daily rainfall distributions.

3.1 Fines and Damages

Municipal stormwater plans do not require cities to meet numeric targets for watershed quality, but cities do have to meet water quality requirements for point source discharges from treatment plants and other facilities (U.S. Code 1987; EPA 1999; CV-RWQCB 2007). The EPA and state environmental regulatory organizations require regular monitoring and assess fines of $10,000 per day for infractions. For instance, if water quality levels from a municipal point source discharge do not meet effluent standards, the municipality is retroactively penalized. The fines are not large but intended to promote municipal actions for maintenance and upgrades. In the model, fines were levied when total runoff volume exceeded stormwater system capacity for a probability-weighted storm.

Property damages can result from urban flooding. Damage costs were included in the model through a simple procedure, which assessed damages of 0-20% of total property costs (per acre) in each region when total runoff volume exceeded stormwater system capacity. The representation of damages is useful but simplified. In reality, more damages result from bigger storms.

3.2 Average rainfall distributions

In any region, rainfall depth varies throughout the year and is subject to uncertainty. For a given region, hydrologic records provide average daily rainfall values. Based on the daily average value, the frequency distribution of rainfall depths for a given day can be modeled as a one-parameter exponential function (Guo & Urbonas 2002):

$$f(D) = \frac{1}{D_m} e^{-D/D_m} \tag{31}$$

Where $D \epsilon \{rainfall\ depths\}$

D_m is the average daily rainfall. The associated probability that a rainfall depth value (d_m) does not exceed D is equal to:

$$P_D(0 \leq d_m \leq D) = 1 - e^{-D/D_m} \tag{32}$$

This is the cumulative distribution of non-exceedence probabilities. The probabilities for single events of depth D can be calculated using upper and lower interval boundaries across the continuous cumulative function:

$$p_D(D_L \leq D \leq D_U) = \left(P_{D_U} - P_{D_L}\right) * dD \tag{33}$$

Sacramento has highly-variable seasonal rainfall. Potential rainfall depths range from 0.0 to 0.5 inches, which was assumed to fall within one hour. Average daily rainfall values were estimated based on a 29-year daily record of rainfall for the Sacramento metropolitan area (WRCC 2013). Table 2 lists the average values by month. Figure 2 shows cumulative probability distributions for representative days in each month.

Figure 2: Cumulative probability distributions for daily average rainfall in Sacramento. Graphs show a representative distribution for one day in each month

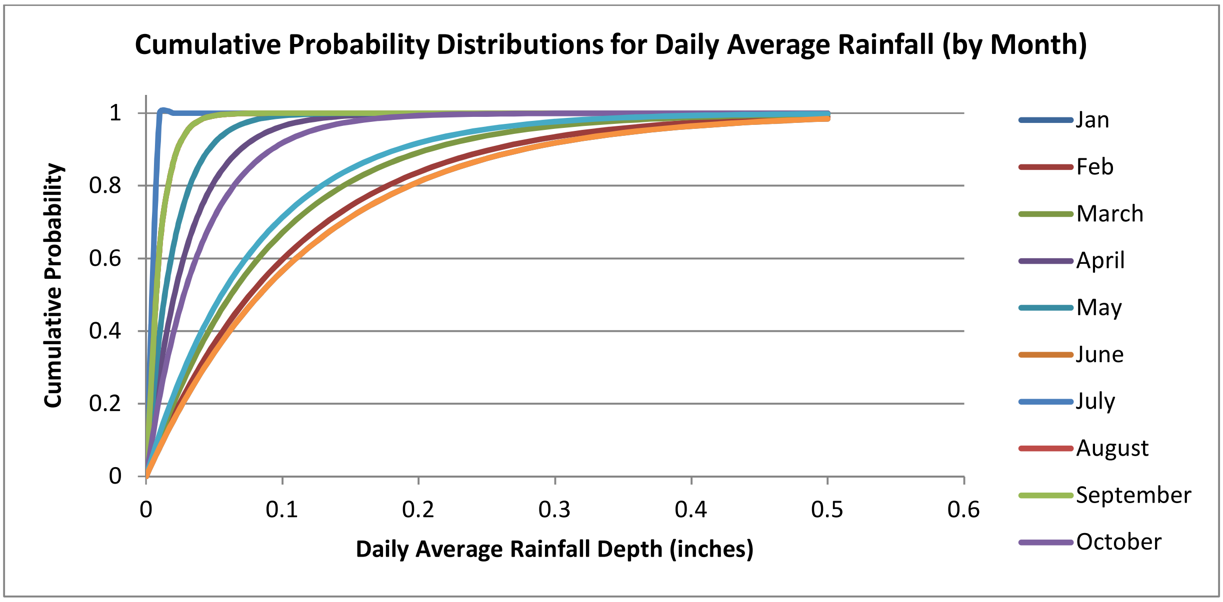


Table 2: Daily and monthly average rainfall values, based on 30-year record (1981-2010) for Sacramento region (Source: Western Regional Climate Center)

Month	Daily Average (Min-Max)	Monthly Average
Jan	0.11-0.13	3.64
Feb	0.11-0.13	3.47
Mar	0.06-0.12	2.75
Apr	0.02-0.06	1.15
May	0.01-0.03	0.68
Jun	0-0.02	0.21
Jul	0	0.0

Aug	0-0.01	0.05
Sep	0-0.02	0.29
Oct	0.01-0.05	0.95
Nov	0.05-0.09	2.08
Dec	0.09-0.12	3.25

3.3 Implementation

I implemented the optimization similar to the Chapter 3 model using the *IBM ILOG CPLEX Studio* Integrated Development Environment (IDE) (IBM 2012). The IDE provides a by Javascript® environment for developing and editing a model that uses the *ILOG CPLEX* optimizer. The *ILOG CPLEX Studio* IDE was obtained through an academic license from IBM. Data was stored and analyzed in Microsoft Excel. I developed *Python* scripts using the open-source *PyScripter* IDE to control input and output procedures to the CPLEX optimization algorithm (Python Software Foundation 2001; Vlahos 2005).

4 Results

Model results indicate that a risk-based analytical framework for stormwater planning with damages and fines can yield stormwater infrastructure with drainage capacity exceeding the target-based case. Damages are the strongest motivation for cities to build stormwater infrastructure.

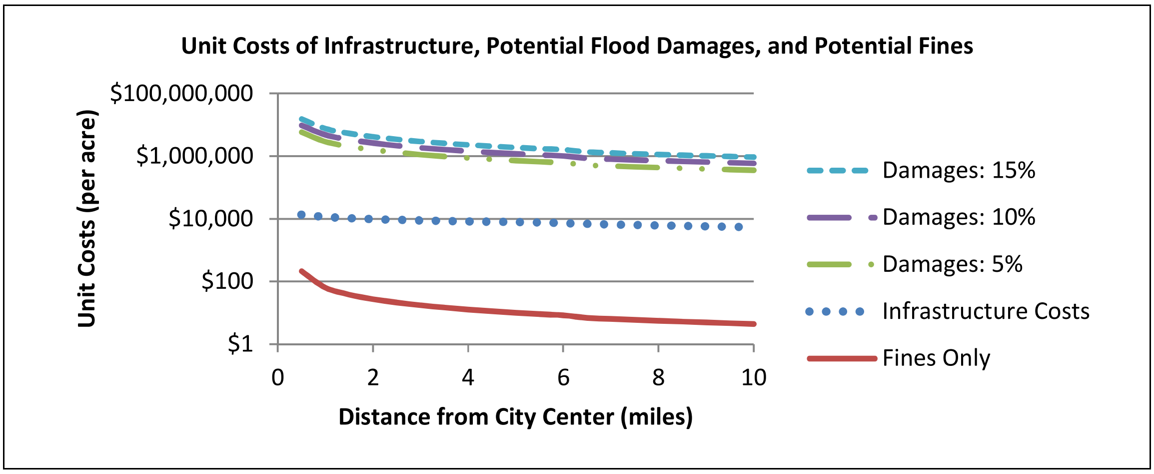
Two different risk-based approaches were assessed:

1) *Fines only,* where cities are assessed $10,000/day with an overflow for insufficient infrastructure
2) *Fines and Damages,* where cities incur both fines and damages (20% of property values) from overflows. Damages were assessed levels ranging from 1% to 20%.

The two risk-based cases were compared to a target-based case, which calculated total system costs for building stormwater infrastructure with sufficient drainage capacity to meet predicted runoff (labeled *infrastructure costs* below).

As shown in Figure 3, minimizing total costs when only considering regulatory fines (#1) resulted in no infrastructure beyond landscape infiltration.

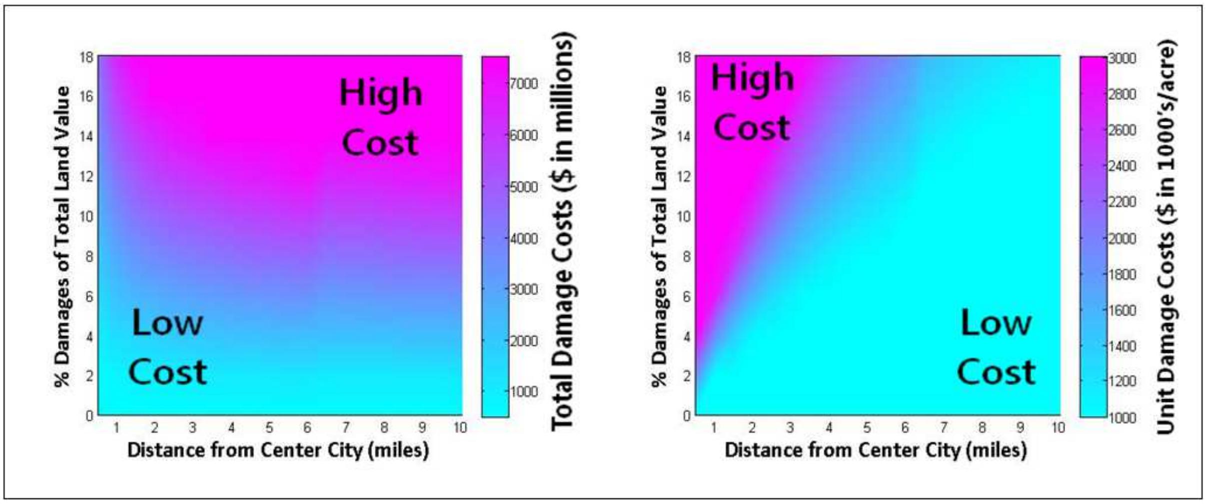
Figure 3: Unit costs of building infrastructure (dashed line), or fines and damages without infrastructure (solid lines). Three potential levels of damages are shown: 5% of land values, 10% of land values, and 15% of land values. Fines alone are insufficient to motivate cities to build infrastructure, but even small consideration of flood damage costs can motivate cities to build stormwater infrastructure to manage runoff.



Current levels of federal fines are too small to spur infrastructure development. However, when considering annualized damage costs (#2) from flooding, stormwater infrastructure becomes optimal to prevent flood damages assessed at even very small percentages of land values. Annualized unit costs for the target-based case (labeled infrastructure costs) ranged from $5,000 to $14,000 per acre, as shown by the dotted line. When damages accrue from overflows, the annualized unit costs for flood damages as percentage of land value (5%, 10%, and 15%) ranged from $1,000,000 to $15,000,000 throughout the region depending on the estimated damage level. Annualized unit costs of fines for overflows were insignificant.

Changes in annualized expected damage costs vary throughout the urban region, as shown in Figure 4. Total annualized expected damage costs are highest in the periphery even though land is less valuable. Unit costs of annualized expected damages, however, are highest from intense storms near the city center.

Figure 4: Total costs (left) and unit costs (right) of annualized expected damages without stormwater infrastructure. Total costs are higher in ex-urban areas, while unit costs are highest near the city center in high-risk areas. Even small values of expected damage costs exceed infrastructure construction costs.



5 Discussion

Model results indicate that cost-effective urban stormwater designs based on flood risks build drainage and infiltration infrastructure to manage runoff. Even small potential damages, especially in expensive areas, motivate cities to invest in stormwater infrastructure. Through the 20th century, U.S. cities did indeed build such infrastructure to minimize flood risks. Over time, policies became codified and centrally-regulated to ensure compliance in both the public and private sector. In coming decades with expected climate variability and potentially larger storms, flood risks will likely continue to motivate innovative stormwater actions in susceptible cities. Renewed interest in coastal protection in cities such as New York and San Francisco illustrates how infrequent but large storms can spur investments. In addition, surface retention and LID will become more popular due to both economics and emerging attitudes in urban planning.

Current stormwater planning procedures mix target-based regulations and risk-based approaches. Yet, this combination, developed over decades, does not guarantee environmental quality. Different levels of government tend to promote different interests for managing stormwater. Municipalities originally built stormwater systems and developed building codes to prevent flood damages without considering environmental quality. Beginning in the 1970's, state and federal regulators promoted water quality requirements. Today, fines for environmental contamination exist but are a weak motivation for cities to build new infrastructure in comparison to potential flood damages. Environmental quality is primarily regulated through municipal stormwater permits, which mandate "best practices" rather than specific water quality outcomes. Stormwater designs must protect urban regions from flood risks and *also* improve environmental quality. Both innovative structural measures (water treatment plants) and enhanced landscapes (green infrastructure) are useful in this multi-objective planning.

Notable improvements in stormwater quality resulted from a combination of federal carrots and sticks. While regulations and permit processes required cities to develop runoff management plans, federal and state grants supplemented the high costs of treating sewage and stormwater. As available funds reduce, cities will again take the lead. This raises an important question for environmental quality: what will motivate cities to undertake measures to reduce pollution and not just manage flood risks? Social attitudes, new approaches for urban design, and green infrastructure benefits for real estate values are all potential motivators. Environmental advocates are pursuing efforts to integrate broader benefits for innovative stormwater management measures into planning procedures. This may be a necessary development to prevent renewed environmental externality problems.

5.1 Limitations

The model presented in this chapter has several limitations similar to those described in Chapter 3. The geographic configuration of the model is overly-simplified. Also, the model only considered runoff volume from a sixty-minute design storm in the 85^{th} percentile, and treatment plants and LID can be better represented. In addition to these limitations, the risk-based approach also had additional simplifications. Damages were assessed independent of overflow volume. A more robust model would incorporate a damage response function based on flood size. Hydrologic uncertainty, which was included as a probability-weighted distribution of rainfall amounts based on daily averages, simplifies the risk of large storms. The hydrology may also change in coming decades with climate variability. Another limitation in the model is that cities had no recourse to minimize flood damages following the initial decision to build flood protection measures. Evacuation, temporary flood walls, and infrastructure hardening can all reduce risks from forecasted floods. Finally, the benefits and costs of actions to reduce risk may go to different actors. For instance, municipal stormwater infrastructure may benefit private landowners, while municipalities pay the majority of construction and management costs. Political and regulatory processes may help to equalize the distribution of these benefits and costs over time.

6 Conclusions

This chapter presented a model to assess the cost-effective mix of conveyance and infiltration measures using a risk-based approach to system design. The model minimized the total costs of building infrastructure along with expected damages and fines from flooding. Results indicated that expected flood damages, assessed as a percentage of land values, spur cities to build stormwater infrastructure. Even small estimates of damage (1% of land values) are sufficient motivators. Environmental quality, however, which was included in the model through potential fines from overflows, is less significant. Coupling flood damages with environmental quality, or increasing the fines levied for overflows, could spur cities to improve infrastructure. Many state and federal agencies use such tactics. For instance, the U.S. EPA has aggressively promoted the use of green infrastructure and innovative stormwater measures through grants, research, education, model development, and regulations for twenty years.

As cities recognize increased risks from climate variability, risk analysis approaches for managing stormwater will grow. Model results can inform urban planning and design. The theoretical framework presented in this chapter can be improved with better representation of green infrastructure and treatment plant construction. Stormwater research can also better characterize risks across cities, such as comparing wet-weather cities with combined sewers to arid cities with surface-based measures.

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Chapter 5

Ecological Resilience and Water Resources

To see complex systems of functional order as order, and not as chaos, takes understanding.

- Jane Jacobs, in The Death and Life of Great American Cities (1961)

Abstract

Resilience is broadly applied across many fields to describe stability and change in systems. *Engineering resilience* emphasizes stability of performance, measured by minimizing deviations from desired outcomes. *Ecological resilience* emphasizes the dynamic nature of persistence and reorganization in systems, acknowledges uncertainty in system states, and emphasizes the importance of connectivity between and within groups of species of similar functions (Holling 1996). The dichotomy of terms has use for understanding complex water resource systems. This chapter reviews literature on resilience and applies the concept of ecological resilience to water resources management. It presents an optimization of a simplified water resources network to analyze the effects of disturbances on cost-effective network configurations. Results illustrate how network configurations are relatively stable under most disturbances, but can exhibit thresholds of change and non-linear responses to external drivers. Large disturbances, such as the loss of a major supply aqueduct to a city, are necessary to induce significant changes in the relative mix of supplies from conveyance imports and alternative sources. The chapter discusses implications of ecological resilience perspectives for long-term management of water infrastructure, links the concept with current research in multi-objective optimization and visualization of water resources, and proposes future extensions of the framework.

1 Introduction

Stability, disruption, and persistence are consistent themes in infrastructure and resource management. Industrialization and urbanization established more stabilized flows of resources, such as water and energy, to promote economic development and public health (Blake 1956; Hughes 1993). In many parts of the Western U.S., consistent access to resources meant securing rights to distant areas and building large and expensive infrastructure. Facilitated by development, water and energy consumption increased steadily throughout the Western U.S. Cities transcended local resource constraints by building large systems that reached far beyond their borders to fuel growth, economic security, and public health improvements (Hundley 2001).

This history of development and urbanization in Western North America, however, is peppered with uncertainty and disruptions. Fires regularly leveled nineteenth- and twentieth-century cities, including Seattle (1889), Vancouver (1886), Houston (1912), and San Francisco (1906). The 1906 San Francisco fire, in particular, followed a destructive earthquake. Local businessmen and political leaders often used such disasters to plan large changes in infrastructure, organizations, and development. In Seattle, for instance, the city undertook a massive building program after the 1889 fire to improve drainage by raising the established downtown area (Speidel 1997). Natural disasters, including floods, droughts, earthquakes, hurricanes, and fires are all disturbance mechanisms that cause significant rebuilding expenses. In the U.S., the federal government subsidizes insurance programs to support economic development in areas of higher risk, including floods and coastal storms (Burby 2001). Other non-environmental disturbances also affect the structure and function of systems, including changes in social attitudes, technological innovations, and political or regulatory decisions. For instance, large-scale revitalization taking place today in many American cities is reorganizing social structures and redistributing wealth. Thus, natural, social, and technological factors all contribute to possible large-scale and potentially disruptive disturbances in the structure and function of infrastructure systems.

The term resilience captures the tension between uncertain disruptive events and policy goals that seek stability. Resilience literature is extensive (Klein et al. 2003; Reghezza-Zitt et al. 2012) to the point of confusion (Klein et al. 2003; Blackmore & Plant 2008). It is applied in many fields (Garbin 2007), including engineering (Fiering 1982a; Hashimoto et al. 1982; Holling 1996; Blackmore & Plant 2008), ecology and natural resources management (Holling 1973; Peterson et al. 1998; Folke et al. 2004), national security and critical infrastructure (McCarthy et al. 2007; National Infrastructure Advisory Council 2009), distributed energy systems (Bouffard & Kirschen 2008), and disaster-related research (Bruneau et al. 2003; Manyena 2006; Chang 2009). Contemporary academic definitions of resilience come primarily from ecology, sociology, and systems engineering, as detailed in Table 1.

Table 1: Definitions of Resilience Across Disciplines

Definition of Resilience	Field	Citation
The ability of the system to absorb changes of state variables, driving variables, and parameters, and persist	Ecology	Holling (1973)
Ecosystems can undergo regime shifts whereby the system moves to a definitively separate state by crossing over a threshold	Ecology	Beisner et al. 2003; Carpenter 2003; Ludwig et al. 1997; Scheffer and Carpenter 2003; Scheffer et al. 2001
(1) The amount of disturbance a system can absorb and still remain within the same state; (2) The degree to which the system is capable of self-organization; and (3) The degree to which the system can build and increase the capacity for learning and adaptation.	Sociology & Ecology	Carpenter et al. (2001)
The capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, and feedbacks	Sociology & Ecology	Walker et al. (2004), Folke et al. (2010)
Describing deviation from a single stability point	Systems Engineering	Holling (1996)
The preservation of routine activities that preserve welfare for communities	Risk Management	Handmer and Dovers 1996
Likely recovery time for a system to return from failure	Water Resources Engineering	Hashimoto et al. (1982)

In water resources, tensions between stability and disturbance are important considerations. Water system managers seek regular supplies and operation, while hydrologic events are inherently uncertain. Large-scale infrastructure systems that bring water to urban, industrial, and agricultural users are expensive and operate for decades. Yet, within the lifespan of such systems, economic and climatic changes can alter system cost-effectiveness. Economies of scale in existing systems that promote stability compete with disruptive trends that drive system improvements. Engineers and infrastructure managers characterize resilient systems as those that "bounce back," while ecologists and environmental practitioners recognize that systems may bounce back or completely reorganize, depending on the collection of disturbance factors. Incorporating this ecological notion of resilience into water resources engineering practice is an important step for the evolution of the field.

1.1 Purpose and questions of interest

Analyzing water resource systems in the context of ecological resilience poses intriguing questions. First, what, if any, alternative system configurations exist that satisfy current demands at reasonable costs? Second, what is a stable operational state for a water resource network? Third, how do both disturbances and path dependence affect optimal configurations of cost-effective designs for an infrastructure network? Finally, do "critical thresholds" exist in system operation and configuration and, if so, how do resource managers identify such thresholds? The analysis seeks to address some of these questions and chart new approaches that challenge current common practices among engineers and policy managers.

This chapter applies the concept of ecological resilience to water resources management. It reviews literature from engineering, ecology, and natural resources management to understand different conceptions of the term resilience. It uses a simple water supply model to test how initial conditions and system disruptions affect cost-effective network configurations. The model optimizes the mix of imported and alternative water sources in a regional water conveyance network for four cases: a system with existing infrastructure (base case); a system requiring new construction; a system with subsidized alternatives; and a system with large disturbances to existing centralized supplies. A sensitivity analysis explores thresholds in system configuration based on water availability and cost. Results highlight important themes for future water resources management and policy, including path dependence, disasters, and technology, which can all be incorporated into analysis using an ecological resilience framework.

2 Resilience in Engineered and Natural Resource Systems

The term resilience entered ecology literature in the early 1970s with debates over the existence of equilibrium points in ecosystems. At the time, ecology literature accepted the existence of system-wide, globally-stable states, which had strong roots in research (Lewontin 1969). Ecosystem managers calculated *maximum sustainable yields,* which are consistent extractions of resources that a system could regularly provide without collapsing (Schaefer 1954). Yet, research in population biology challenged the view that ecosystems achieved long-term equilibrium (Sutherland 1974).

In time, research recognized that ecosystems have periods of instability, which are linked to a system's complexity as well as disruption from external effects (Pimm 1984). These insights were seminal. Holling (1973) proposed that ecosystems move between periods of stability and change, describing "resilience" in ecosystems as the ability of the system "to absorb changes of state variables, driving variables, and parameters, and still persist." *Stability,* on the other hand, was "the ability of a system to return to an equilibrium state after a temporary disturbance." Linear systems, or non-linear systems close to a local stability point, can often be treated as having a global optimum, but disturbances can cause unexpectedly large changes (Holling 1986; Rogers & Fiering 1986; Pimm 1991). Ecosystems transition over time through multiple configurations of species composition and interaction (Klein et al. 2003; Blackmore & Plant 2008) and may remain in either local or global points of stability (Ludwig et al. 1997). The collection of potential states themselves can be dynamic (Peterson et al. 1998; Folke et al. 2002, 2010).

More recently, research in resilience has examined and critiqued human policies for managing natural resource systems. Managing for *engineering resilience* seeks regulated performance to minimize deviations from a desired target, which supports economic planning. In contrast, managing for *ecological resilience* recognizes that systems are not stable. Disturbances can alter the structure and function of systems, possibly leading to a new operational state (Holling 1996). For instance, an ecosystem may be permanently transformed from a forest to grassland through a singular disturbance, such as a fire, or through a combination of incremental and sudden disturbances such as fire, climate change, and human agricultural practices.

Changes in ecosystem states, often called regime shifts, occur when systems cross a threshold to a new state (Ludwig et al. 1997; Scheffer et al. 2001; Beisner et al. 2003; Carpenter 2003; Scheffer & Carpenter 2003). *Thresholds* are definitive and irreversible, while *transitions* between states of an ecosystem may be either reversible or irreversible without human interventions (Stringham et al. 2003). State-and-transition models (STMs) in ecology identify thresholds and shifts between alternate states (domains of climate, soil, and vegetation) and are increasingly used to understand how ecosystems changes result from both human actions and natural events (Westoby et al. 1989). States are typically defined in relation to human management. Models use current and historical ecological data to characterize different possible states of a local site and determine factors that can move it between states (Westoby et al. 1989; Stringham et al. 2003).

Though ecological management recognizes the possibility of system shifts, water resource managers typically emphasize stable supplies and optimal outcomes. This is true in both theoretical literature and applied practice. Hashimoto et al (1982) first outlined definitions for resiliency, reliability, and vulnerability in a water system to assess alternative designs and operational performance. They defined: *reliability* as the probability, α, that a system is in a satisfactory operational state, with only two possible states, operation or failure; *vulnerability* as the likely magnitude of failure, when failure occurs; and *resiliency* as the likely system recovery time following failure, (drawing closely on *stability*). Resiliency, γ, is given by:

$$\gamma = \frac{\rho}{1-\alpha} = \frac{Prob\ [\ System\ Fails\ in\ time\ t\ but\ Operates\ in\ previous\ time\ step\ (t-1)\ ]}{Prob\ [\ System\ Failure\ in\ time\ t\ \ ]} \quad (1)$$

The reciprocal $(1/\gamma)$ of Equation 1 is the average recovery time from failure. At the same time, Fiering (1982a, 1982b, 1982c) surveyed many possible formulations of resilience in water resources, classifying potential metrics by two main approaches: 1) metrics that measure how far a system is from a critical threshold, and 2) metrics that measure changes in the possible landscape of potential system states over time (Fiering 1982a; Wang et al. 2009). Subsequent water resources research characterized benefits and tradeoffs between these conceptions of reliability, resilience, and vulnerability, (Moy et al. 1986; Kundzewicz & Laski 1995; Vogel & Bolognese 1995; Vogel et al. 1999; Kjeldsen & Rosbjerg 2004; Wang et al. 2009). The majority of research and practices, however, focus on single system components or *engineering resilience* conceptions that minimize deviations from expected outcomes.

2.1 A role for *ecological resilience* in water resources management

Even as the *engineering resilience* approach dominates water planning, large disturbances such as floods and droughts can have wide effects on operational efficiency. More broadly, environmental factors interact with social attitudes and technological systems to promote or hinder potentially disruptive risks. Water resources management often seeks to stabilize outputs, but in an era of climate change, both hydrologic variability and new technologies may push water resource networks into new configurations. Even conceptions of sustainability in water resources, which have developed over nearly two decades, embody this tension between *stability* and *transition*. Sustainable water resource systems are defined as those that "contribute fully to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity" (Loucks 1997). Thus, for some, maintaining environmental and hydrological integrity implies a static environment, while others argue that integrity must consider changing ecosystems.

Understanding system thresholds and the possibility for system reorganization can bridge competing needs for predictable outcomes and operational flexibility, while informing water resources planning. Throughout the U.S., regional networks of water infrastructure with technological, environmental, and social elements, developed to regulate environmental variability and ensure water deliveries. Typical practices seek stability of performance, but managers increasingly recognize the potential short-term (droughts) and long-term (social attitudes and climate change) drivers of change in available resources. Initial conditions, disruptions, social attitudes, and technology all influence decision-making. California, in particular, has an extensive system of water conveyance through aqueducts, canals, and rivers, which developed over decades and provides a useful inspiration for analyzing applications of ecological resilience in water planning.

3 Model Formulation: Transitions in a Water Supply System

In a regional water distribution system, managers choose combinations of conveyance infrastructure and alternative local sources to obtain water supplies that meet residential, commercial, and industrial demands, D_k, in each urban region, k, of the system.

Conveyance options consist of S canals, aqueducts, and natural rivers that can provide a water supply, Q_{ik}, to one of R regions up to the maximum limit of each source, $Q_{ik_{max}}$. The presence or absence of connections between source i and region k is specified by a matrix of binary variables (P_{ik}) that represent conveyance decisions in a link-node network. Alternative source options of A local and technological alternatives include local surface water, groundwater pumping, desalination, direct reuse, and conservation.

A mixed-integer linear program minimizes the total cost of meeting water demands by selecting the low-cost mix of conveyance and alternative options using two sets of decision variables: 1) a binary variable, X_{ik}, for conveyance infrastructure links between source i and region k, which determines the flow volume, $Q_{ik}(X_{ik})$, from source i to region k; and 2) a continuous variable, Q_{jk}, for the volume supplied by alternative source j to region k. The formulation identifies the cost-effective mix of options, based on a total cost Z:

$$Min\ Z = \sum_{i=1}^{S}\sum_{j=1}^{A}\sum_{k=1}^{R}\left[\left(C_i Q_{ik}(X_{ik})\right) + \left(C_j Q_{jk}\right)\right] \tag{2}$$

where $S \epsilon \{conveyance\ sources\}$
$A \epsilon \{alternative\ sources\}$
$R \epsilon \{regions\}$

The cost for conveyance and alternatives is calculated using annualized unit costs for supplying water through conveyance infrastructure (C_i) and alternative sources (C_j). Water supplies must meet the total demands in a region:

$$\sum_{i=1}^{S}\sum_{j=1}^{A} Q_{ik}(X_{ik}) + Q_{jk} \geq D_k \tag{3}$$

Conveyance infrastructure provides flow up to the maximum capacity from source i to region k when the decision variable is equal to 1, but only when the binary matrix constraint, P_{ik}, is also equal to 1:

$$Q_{ik}(X_{ik}) \leq Q_{ik_{max}} \tag{4}$$

$$X_{ik} \leq P_{ik} \tag{5}$$

The volume of water supplied through alternative sources is limited by source and region. Many cities in California and the west exhausted local surface and groundwater supplies by the early 20th century. In the model, local surface and groundwater supplies were limited to estimated 1920 urban demands (see Section 4.2.1):

$$Q_{jk} \leq D_{k_{1920}} \tag{6}$$

$$\text{when} \quad j\ is\ surface\ water, groundwater$$

Water reuse was also limited by total demands, since a locality cannot reuse more water than it has locally available.

$$Q_{jk} \leq D_k \tag{7}$$

$$\text{when} \quad j\ is\ reuse$$

Conservation was limited to a maximum of 20% of total current demands, based on general discussions with system managers. Conservation is often used as an effective tool to manage water shortages during droughts but it is subject to social and technological limitations. The final alternative source, desalination, was not limited for coastal cities.

$$Q_{jk} \leq .2 * D_k \tag{8}$$

$$\text{when} \quad j\ is\ conservation$$

The annualized unit cost for conveyance infrastructure, C_i, includes construction and treatment costs:

$$C_i = C_{i_c} + C_{i_t} \tag{9}$$

The unit cost for water treatment, C_{i_t}, is equal for all sources ($200/ac-ft). The annualized unit cost for construction, C_{i_c}, is estimated over a long lifespan using the original construction cost, $C_{i_{orig}}$, a discount rate r of 5%, and the maximum flow capacity, $Q_{ik_{max}}$, such that:

$$C_{i_c} = \frac{C_{i_{orig}} * r}{Q_{ik_{max}}} \tag{10}$$

Water supplied through alternative sources, C_j, has an annualized unit cost of construction, C_{j_c}, based on typical construction costs for treatment, desalination, and pumping plants, as well as a unit cost of delivery typical of each source, C_{j_d}:

$$C_j = C_{j_c} + C_{j_d} \tag{11}$$

Finally, continuous decision variables are subject to non-negativity constraints:

$$Q_{jk} \geq 0 \tag{12}$$

Table 2 lists all parameters included in the model. Figure 1 illustrates the simulated network structure, which includes 5 canals, 2 rivers, and 4 aqueducts that supply 6 cities.

Table 2: Decision variables and parameters included in model

Parameters	
D_k	Water demands in region k
Q_{ik}	Flow capacity from source i to region k
$Q_{ik_{max}}$	Maximum flow capacity from source i to region k, specified by river size or infrastructure capacity
P_{ik}	Binary parameter indicating existing infrastructure links that supply water from source i to region k.
C_i	Annualized unit cost of water supply through existing conveyance infrastructure from source i
C_{i_c}	Annualized unit costs for construction of water supplied through existing conveyance infrastructure from source i
C_{i_d}	Unit costs for water treatment for water supply via existing conveyance infrastructure from source i
$C_{i_{orig}}$	Original construction costs of large scale infrastructure for source i
C_j	Total unit delivery cost of water from alternative source j
C_{j_c}	Unit delivery cost of water from alternative source j associated with annualized construction costs
C_{j_d}	Unit delivery cost of water from alternative source j associated with delivery, treatment, and pumping
r	Discount rate
Decision Variables	
X_{ik}	Binary variable indicating if the existing infrastructure project that moves water from source i to region k is selected in the cost-effective mix.
Q_{jk}	Continuous variable indicating the volume of water supplied from alternative source j to region k

3.1 Analysis Cases

The analysis included a base case of existing infrastructure and several extensions formulated to test the possibility of significant system "reconfiguration" from different influences and disturbances, as summarized in Table 3. In the base case of *Existing Infrastructure*, conveyance infrastructure costs are annualized based on prior construction. The case represents a "business-as-usual" situation and emphasizes the role of path dependence.

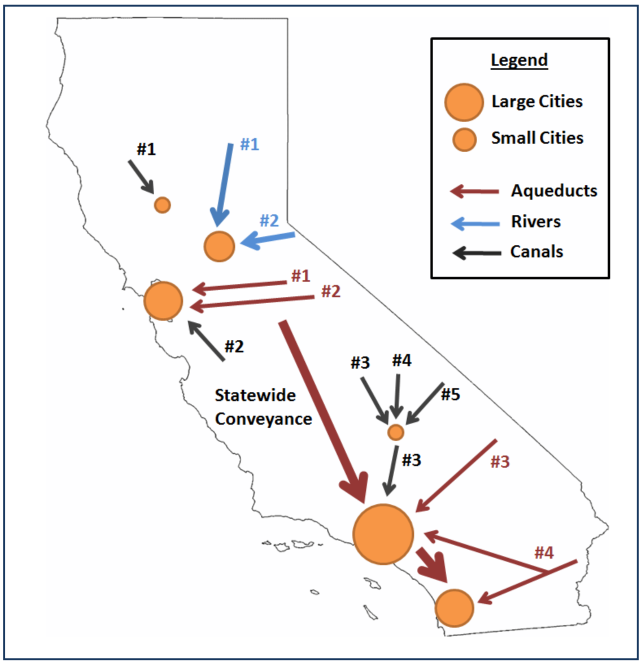
The extension cases included: *New Infrastructure, Subsidized Alternatives,* and *Missing Links*. Each extension simulates a potential external driver of system change to understand its effects and explore the potential for system reorganization. In the first extension case of *New Infrastructure*, annualized construction costs for conveyance sources were based on the present-day cost of building similar infrastructure. Instead of benefiting from prior investments, regions must make decisions between construction and alternative sources. In the second extension case of *Subsidized Alternatives*, conservation, reuse, and desalination are subsidized through reduced unit costs of supply to simulate policies that seek to improve affordability.

Finally, in the *Missing Links* extension case, regions face reduced or no supplies from existing infrastructure and must use alternative water sources.

Table 3: Description of cases included in the analysis. The *Base* Case has existing infrastructure, while extension cases include *New Infrastructure, Subsidized Alterative Sources,* and *Missing Links.* Each case has construction and treatment costs for water supplies from both large-scale conveyance infrastructure and alternative sources

Base Case	Description
Existing Infrastructure	Conveyance Sources: Annualized sunk unit costs, based on prior construction. Constant treatment delivery costs Alternative Sources: Annualized sunk unit cost of constructing plant facilities; Unit costs of delivery based on source-specific values
Extension Cases	**Differences from Base Case**
New Infrastructure	Conveyance Sources: Annualized unit costs, based on current cost of construction.
Subsidized Alternatives	Alternative Sources: Unit costs of delivery are reduced (by half) to simulate subsidies for promoting alternative sources.
Missing Links	Conveyance Sources: Available supplies from existing conveyance infrastructure (base case values and costs) are reduced.

Figure 1: Network structure represented in the water supply model, superimposed on a map of California to show the major sources and links simulated in the model. Water sources are located in the north and east (inland), while water most users are located in the south and west. Conveyance supplies (aqueducts, rivers, and canals) are delineated by colors, which supply cities. The labels (i.e. canal #1) correspond with labels in Section 3.2.2 below.



3.2 Parameters and Implementation

Model parameters were estimated based on typical costs for water delivery, treatment, and infrastructure development in California.

3.2.1 Conveyance links in network

The capacities for various links in the network were based on published values for major conveyance structures in California, such as the Hetch Hetchy Aqueduct, the California Aqueduct, the Los Angeles Aqueduct, and the Tehama-Colusa Canal. Total construction costs for each conveyance link, however, did not necessarily reflect actual historical construction costs. Infrastructure was assumed to be long-lived for discounting purposes. Table 4 lists the parameters associated with each link.

3.2.2 Water demands

Model parameters included estimates for water demands based on current and historical per capita use in the San Francisco Bay Area, which were then applied to all urban users. Per capita use increased from approximately 75 gallons per day (gpd) to 160 gallons per day for residential users between 1930 and 2000 (EBMUD 2013). Figure 2 illustrates this historical data.

Table 4: Conveyance infrastructure parameters for links included in the network model

Name	City/Region	Flow Capacity (ac-ft/mo)	Annualized Cost (million $)	Annualized Unit Cost ($/ac-ft)
Canals				
Canal 1 (north)	North	118,356	$2.5	21.1
Canal 2 (central)	Central to Coast	8,333	$1.25	150.0
Canal 3 (south)	Coast to South	177,534	$1.25	7.0
Canal 4 (south)	South	887,671	$5	5.6
Canal 5 (south)	South	295,890	$25	84.5
Rivers				
River 1	Central	6,800	$0	0
River 2	Central	14,208	$0	0
River 3	Central	333,333	$0	0
Urban Aqueducts				
Temperate City Aqueduct 1	East to coast	17,753	$6.75	380.2
Temperate City Aqueduct 2a	East to coast	5,918	$6.75	1,140.6
Temperate City Aqueduct 2b	East to coast	8,877	$1.25	140.8
Temperate City Aqueduct 2c	East to coast	14,795	$5	337.9
Arid City Aqueduct 3a	North to South	29,589	$10	337.9
Arid City Aqueduct 3b	North to South	17,753	$4.45	250.6
Arid City Aqueduct 3c	North to South	88,767	$20	225.3
Arid City Aqueduct 4a	East to South	11,836	$3.75	316.8
Arid City Aqueduct 4b	East to South	14,795	$1.25	84.5
Arid City Aqueduct 4c	East to South	23,671	$1.25	52.8
Inter-Regional Aqueducts				
Inter-regional Aqueduct	North to south	887,671	$75	84.5

Urban per capita demands from 1990 (160 gpd) were multiplied by the population of each region to determine total demands for region k (Table 5). In the real system, per capita use from inland communities is typically higher due to higher temperatures and larger lot sizes, which promote more evaporation (Hanak & Davis 2006). For purposes of the model, though, all users were assumed to have similar per capita demands.

Figure 2: Urban per capita demands from 1920-2000, based on data from the East Bay Municipal Utility District (EBMUD). Per capital demand estimates for 1990 levels were used to estimate urban regional demands in all areas. (* = estimated)

Year	Per Capita Use (GPD)
1920*	65.00
1930	76.09
1940	84.78
1960	156.44
1980	188.14
1990	160.00
2000	166.15

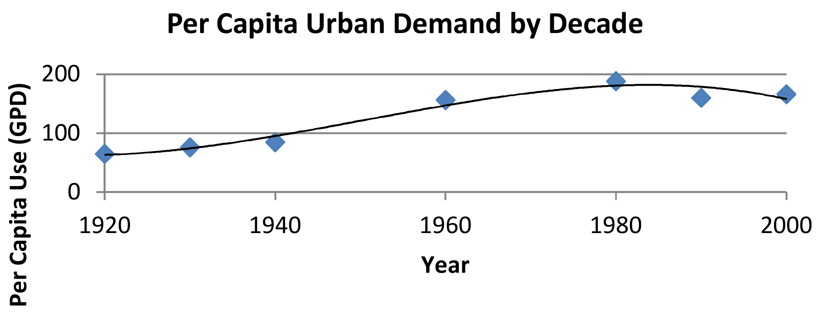


Table 5: Population and total water demand by urban region, as modeled

Region	Total Population	Total Demands (ac-ft/mo)
Rural Cities: North	127,751	1,882
Temperate Northern City	946,287	13,939
Temperate Coastal City	3,566,112	52,531
Rural Cities: South	2,016,441	29,704
Arid Southern City 1	11,090,405	163,369
Arid Southern City 2	2,279,715	33,582

3.2.3 Water supplies

Both conveyance and alternative supply sources have costs for construction and delivery. For conveyance sources, annualized construction costs vary as described in Section 3.2.2, but treatment costs are $200/ac-ft for all sources (LADWP 2010). For alternative sources, construction costs were estimated based on typical project expenses to build plants and facilities for each source, as shown in Table 6. For instance, unit construction costs for desalination were estimated using construction expenses and daily production volume for the Carlsbad Desalination Plant in Southern California (SDWCA 2012). Similarly, construction costs for treatment and reuse plants were estimated using costs and capacities for the Hyperion and Terminal Island plants (LA DPW 2013a, 2013b). Average delivery costs were adapted from research (Hanak et al. 2011).

Table 6: Unit costs for construction and delivery of conveyance and alternative sources

Source	Unit Costs (Thousand $/ac-ft)		
	Construction	Delivery/Treatment	References
Conveyance Sources	See Table 4	$200	Various, LADWP 2010
Alternative Sources			
Local surface water	$46	$0.4	LADWP 2013, Hanak et al 2011
Local groundwater	$30	$0.2	Sacramento County, Hanak et al 2011
Desalination	$140	$1.2	SDCWA 2012, Hanak et al 2011
Reuse	$55	$1.0	LADWP 2013, Hanak et al 2011
Conservation	$0	$0	Hanak et al 2011

Local surface water and groundwater supplies were limited to historical water consumption in California cities. The maximum available supplies from these sources (local surface water and groundwater) were set equal to 1920 demand estimates (Section 3.2.2) for each region. The associated percentage of current demand met by these volumes varied from 1-6%, as shown in Table 7. Additionally, conservation could meet up to 20% of regional demands, while desalination did not have associated constraints.

Table 7: Supply capacity limits for alternative sources

Region	Alternative Supply Sources (ac-ft/mo)					
	Max <6% of local demands (based on source)				Max 20% of local demands	
	Local Surface Water	Local Groundwater	Reuse	Max % of Current Demands	Conservation	Max % of Current Demands
Rural Cities: North	83	83	83	2.5%	376	20%
Temperate Northern Metropolis	394	394	394	1.7%	2,788	
Temperate Coastal Metropolis	5,394	5,394	5,394	6.0%	10,506	
Rural Cities: South	1,164	1,164	1,164	2.3%	5,941	
Southern Coastal Metropolis 1	5,106	5,106	5,106	1.8%	32,674	
Southern Coastal Metropolis 2	545	545	545	0.95%	6,716	

3.3 Implementation

I implemented the model using the IBM CPLEX Interactive Development Environment (IDE) v. 12.6. CPLEX received data input from a *Microsoft Excel* spreadsheet file and exported results to a series of spreadsheets, which formatted and graphed results.

4 Results

The algorithm identified optimal allocations of supplies from centralized conveyance and alternative sources. In the base case and each extension case, optimal allocations maximized use of existing conveyance infrastructure. Generally more expensive alternative supplies were used only when existing conveyance infrastructure could not meet demands.

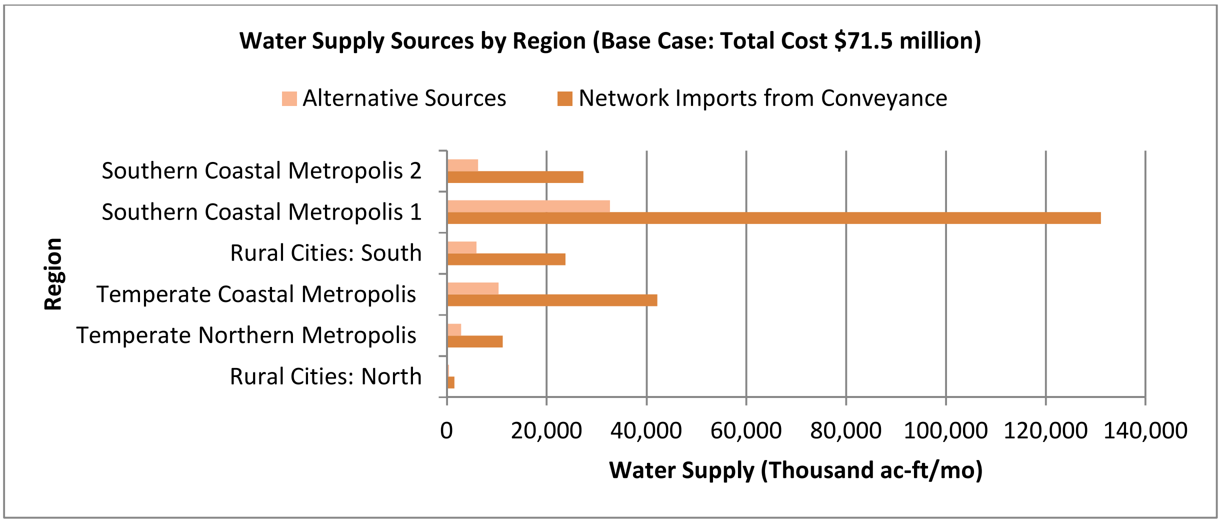
4.1 Summary

Results indicated that optimal network configurations maximized the use of existing network links for three cases: *Base Case (Existing Infrastructure), New Infrastructure,* and *Subsidized Alternatives*. For all regions in these cases, the majority of demands were supplied by water imports. Total costs and the mix of supplies were equal in the *Base Case* and *Subsidized Alternatives* cases (total cost: $71.5 million/month). Conservation is the only alternative source chosen, being maximized because it is "free." Allocations through the *New Infrastructure* case were similarly dominated by conveyance imports, though costs were due to higher unit construction costs (total cost: $145 million/month). Finally, in the *Missing Links* scenario, existing imports to coastal cities are reduced by two-thirds (66%). Yet, the supply reductions are insufficient to force wide use of alternatives beyond conservation, so total costs are relatively stable (total cost: $73.6 million/month). Figure 3 shows water supply sources by region for the base case. Table 8 details the allocations and costs for allocating supply in each case.

Table 8: Model results for supply allocations and costs across cases

	Total Demand (ac-ft/mo)	Supplies by Source (ac-ft/mo)			Annualized Costs for Conveyance Supplies (Thousand $/Mo)		Annualized Costs for Alternative Sources Supplies (Thousand $/Mo)	
		Total Supply	Conveyance	Alternative Sources	Construction	Treatment and Delivery	Construction	Treatment and Delivery
Existing System (Base Case)								**Total Cost: $71,542**
Rural Cities: North	1,882	1,896	1,520	376	$38	$304	$0	$0
Temperate Northern Metropolis	13,939	13,942	11,155	2,787	$0	$2,231	$0	$0
Temperate Coastal Metropolis	52,531	52,532	42,160	10,372	$13,656	$8,432	$0	$0
Rural Cities: South	29,704	29,704	23,760	5,944	$803	$4,752	$155	$1
Southern Coastal Metropolis 1	163,369	163,694	131,040	32,654	$7,665	$26,208	$0	$0
Southern Coastal Metropolis 2	33,582	33,582	27,360	6,222	$1,825	$5,472	$0	$0
New Infrastructure Case								**Total Cost: $145,044**
Rural Cities: North	1,882	1,882	1,625	257	$117	$325	$0	$0
Temperate Northern Metropolis	13,939	13,942	11,155	2,787	$0	$2,231	$0	$0
Temperate Coastal Metropolis	52,531	52,532	42,030	10,502	$68,825	$8,406	$0	$0
Rural Cities: South	29,704	29,704	23,760	5,944	$876	$4,752	$155	$1
Southern Coastal Metropolis 1	163,369	163,374	131,040	32,334	$22,995	$26,208	$0	$0
Southern Coastal Metropolis 2	33,582	33,582	27,040	6,542	$4,745	$5,408	$0	$0
Subsidized Alternatives Case								**Total Cost: $71,542**
Rural Cities: North	1,882	1,882	1,520	362	$38	$304	$0	$0
Temperate Northern Metropolis	13,939	13,940	11,155	2,785	$0	$2,231	$0	$0
Temperate Coastal Metropolis	52,531	52,532	42,160	10,372	$13,656	$8,432	$0	$0
Rural Cities: South	29,704	29,704	23,760	5,944	$803	$4,752	$155	$1
Southern Coastal Metropolis 1	163,369	163,694	131,040	32,654	$7,665	$26,208	$0	$0
Southern Coastal Metropolis 2	33,582	33,582	27,360	6,222	$1,825	$5,472	$0	$0
Missing Links Case								**Total Cost: $73,642**
Rural Cities: North	1,882	1,896	1,520	376	$38	$304	$0	$0
Temperate Northern Metropolis	13,939	13,942	11,155	2,787	$0	$2,231	$0	$0
Temperate Coastal Metropolis	52,531	52,532	37,500	15,032	$14,561	$7,500	$135,804	$906
Rural Cities: South	29,704	29,704	23,760	5,944	$803	$4,752	$155	$1
Southern Coastal Metropolis 1	163,369	163,694	131,040	32,654	$7,665	$26,208	$0	$0
Southern Coastal Metropolis 2	33,582	33,582	27,360	6,222	$1,825	$5,472	$0	$0

Figure 3: Least-cost mix of conveyance and alternative sources across regions in the *Base Case.* Conveyance sources are maximized. Alternative sources comprise the balance of demands in each region, but the only alternative chosen is conservation, due to its low cost.

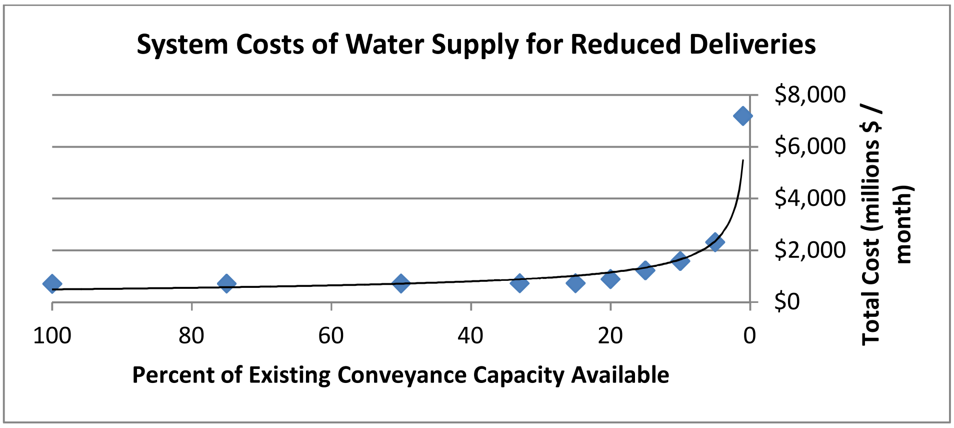


4.2 Sensitivity and Threshold Analysis

To test the effects of water supply reductions from conveyance sources on overall system costs, a sensitivity analysis extended the *Missing Links* case above to vary available supply from existing conveyance structures as a percentage (0-100%) of the full capacities of one major link to each large city: the *Temperate City Aqueduct #1* and the *Inter-regional Aqueduct* (see Table 4). The sensitivity analysis tested: 1) the nature of response to reductions in existing system capacity; and 2) the presence of thresholds in system parameters such as cost.

Results indicate that: 1) costs increase with reductions in existing supply and more expensive alternatives are needed as existing capacity decreases; and 2) a threshold exists (approximately 25% of existing capacity) beyond which system costs increase and alternative source use grows (Figure 4).

Figure 4: Total system costs (conveyance and alternative sources) for decreasing percentages of available supplies through existing conveyance links.



Yet, alternative sources are not adopted at rates greater than 30%, even given the loss of a major infrastructure link for each large city. Cities maximize conservation and increase imports from other links with surplus capacity to meet demands.

Other than conservation, cities turn to alternatives only after passing thresholds in supply reductions of approximately 25% (temperate coastal city) and 15% (arid coastal city) of major links, as shown in Figure 5. The need for alternative sources significantly increases total costs. In the temperate arid city, to make up for conveyance losses, local groundwater provides additional capacity. In the larger southern coastal city, once additional supplies from central conveyance links are no longer available, additional local groundwater, local surface water, and desalination are all used.

5 Discussion

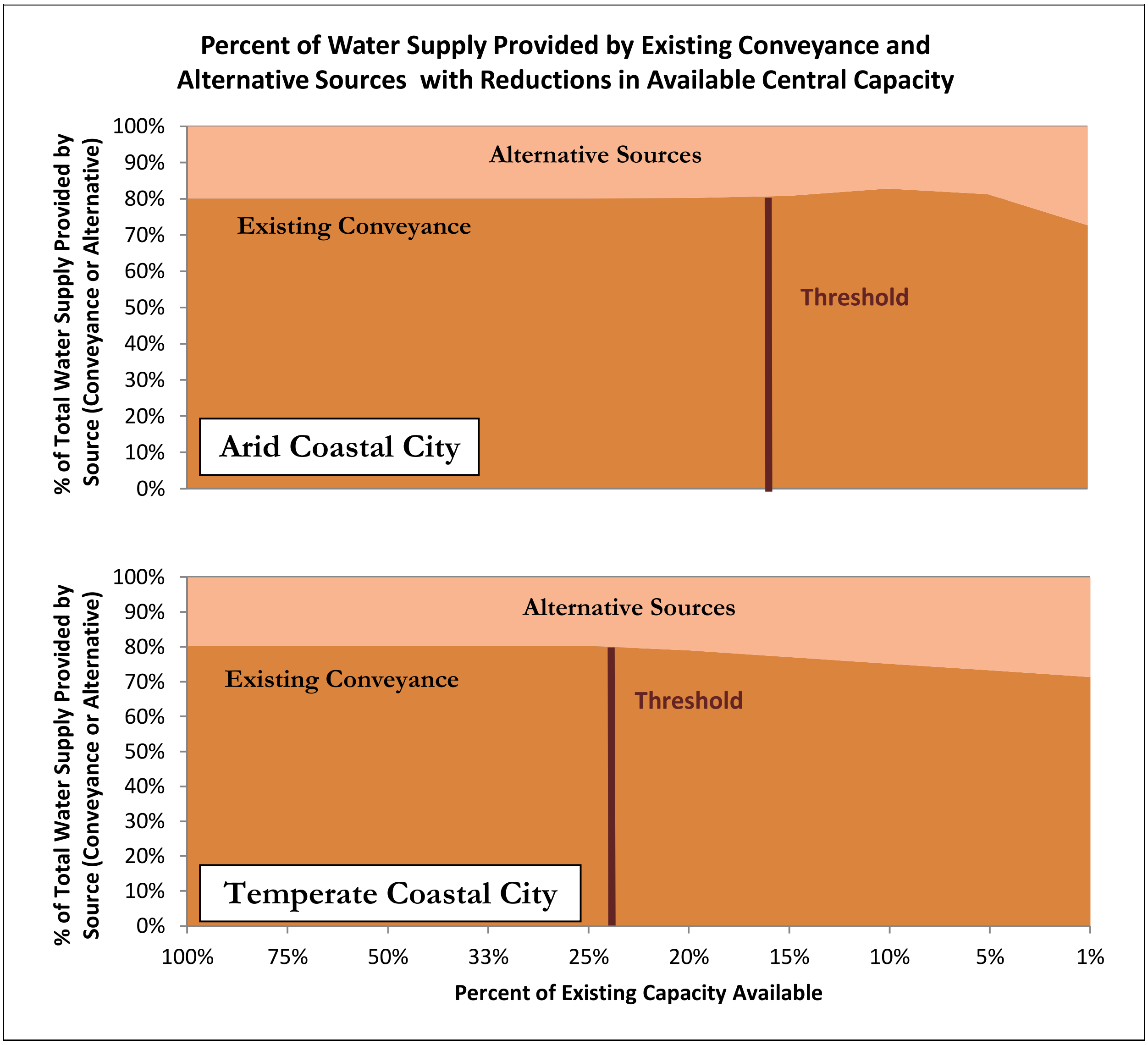
Results showed that large changes to current "operational states," i.e. the mix of existing imports and local alternative sources supplying urban users in the network, are possible following sufficient disturbance in existing operations. Yet, significantly different optimal allocations only emerge from large supply disruptions. Prior investments influence management decisions by reducing the operating costs associated with currently-used infrastructure. For water infrastructure in many parts of the Western U.S., prior investments during earlier eras with different technologies and social attitudes focused on large-scale conveyance to supply cities. Path dependence in the form of prior investments reinforces the use of existing options, even given subsidies for new alternatives. Moreover, even if no infrastructure exists, the long lifespan of water resource projects, along with the current costs and supply limitations of alternatives, motivates cities to continue using traditional "distant" sources.

Large, unrecoverable disruptions to existing infrastructure can alter the mix of optimal supply allocations. The sudden (immediate) or steady (over time) loss of supplies from a major link are one type of disruption that can drive large water users such as cities to consider wider adoption of alternative supply sources. Conservation is the first alternative supply option chosen. While conservation incurred no costs in the model, in reality, long-term conservation programs reduce utility revenues, which is another example of path dependence. Additional local surface and groundwater sources are subsequently tapped, though such sources are likely very limited or already allocated. Desalination and reuse technologies, meanwhile, are choices of last resort due to high energy costs and social attitudes. If capital is more expensive or unavailable, as is the case in many emerging economies, some alternative sources may look more appealing.

The simple network model has analogies for the California water distribution system. Past investments of state and federal monies funded the large-scale infrastructure networks in place today. Cities rely on these conveyance links for cost-effective water supplies. Larger cities such as San Francisco and Los Angeles receive a majority of supply from large links, but also maintain a variety of other sources and agreements to manage uncertain supplies in years of low rainfall. In the model, the thresholds that emerged for wider use of alternative sources were directly related to existing capacities. For the larger southern city (analogous to Los Angeles), the large conveyance link had excess capacity that could be tapped to forgo system shifts to alternatives.

In the actual system, this is analogous to the city injecting surplus surface water into storage aquifers (groundwater banking) or arranging to purchase water through agreements with other uses (farmers or smaller cities). The temperate coastal city (analogous to San Francisco) reaches a threshold of alternative use earlier, as the excess capacity of its major infrastructure link is smaller. These results give insights to the function and structure of a water resource network within the context of complexity and ecological resilience, but the analogy to California water resources should remain limited given the additional environmental and social complexity of California water not included in the simple illustrative network model. The illustrative model can be extended by incorporating more real-world parameters, including agricultural demands and accurate original costs of building the infrastructure.

Figure 5: Sensitivity analysis results for water supply sources in two urban regions. Each city shows a threshold (a percentage of water supplies available from existing conveyance), beyond which alternative sources other than conservation are increasingly used. The slight rise in existing conveyance sources for the arid coastal city (top) results from the binary nature of source selection.



Resilience theory proposes that the nature of connections in an ecosystem influences its tendency for stability or change (Peterson et al. 1998). Complex systems, such as cities, food webs, and economies, have particular characteristics, including non-linear behavior, thresholds, emergence, and feedback. For water resources infrastructure, small changes, such as the slow degradation of levees, may not affect system function and configuration over wide range of potential operating states. Yet large disturbances, such as a flood or drought, can instigate system reorganization and change. Results from the network water supply system model show how small changes in supply, subsidies, and even the presence of existing infrastructure have limited impacts on overall operation. Broad changes in system configuration only developed through very large disturbances (25% or more reductions in existing large conveyance links).

The results compare to state and transition models of ecosystems. Singular, small perturbations may not significantly change species composition or interaction in an ecosystem, but systems can reorganize from a combination of many small changes, a large disturbance, or natural environmental variability. Examples of such combinations of factors exist within water resources. For instance, Hurricane Katrina in New Orleans spurred large-scale inter- and intra-urban population changes. Hurricane Sandy in New York City, though much smaller, was uniquely devastating and instigated broad policy discussions for metropolitan climate change actions. Large events can interrupt path dependence by destroying or damaging prior investments and spurring new capital through rebuilding that changes system economics. Sudden disruptive events include natural disasters (floods, droughts, earthquakes, hurricanes, etc), rapid policy changes, technological failures, or human actions such as terrorism. Yet, large events often compound with incremental factors such as changes in population, climate, rainfall, technology, economics, social attitudes, and infrastructure health. Iterative changes erode the "disruption gap." Thus, the combination of incremental changes, long-term changes, and sudden disturbances can push a system past thresholds and induce large-scale system reorganization to a new "operational state."

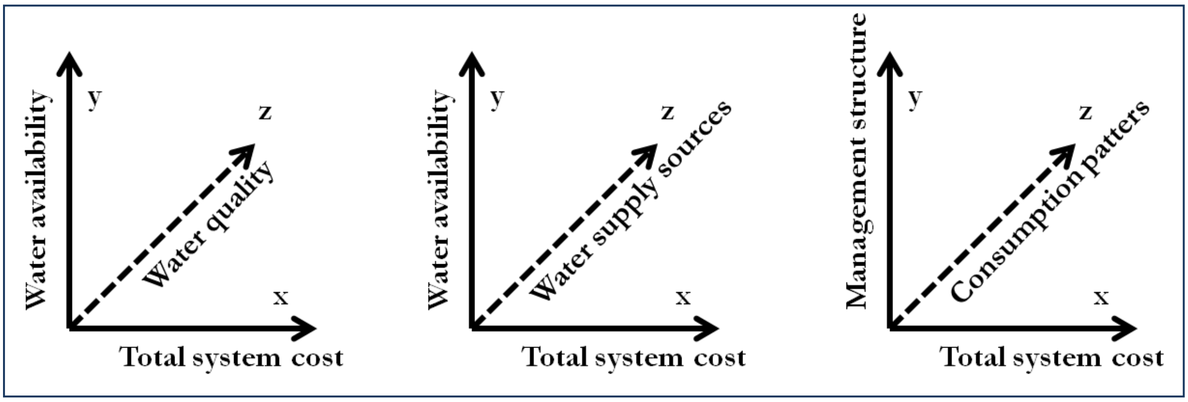
A system-specific transition model for engineered systems can characterize operational states, thresholds, and the variety of factors that drive or inhibit transitions between states. Gradients along a variety of factors characterize operational states, including management structure, water supply sources, the degree of local reliance, consumption patterns of end-users, water quality, and climate and rainfall conditions. Transitions between possible operational states may result from changes in rainfall patters, social attitudes, and technologies, while transitions are inhibited by regulatory structures and path dependence in existing technologies, infrastructures, and institutions. Notably, ecosystem constraints can inhibit transitions when, for instance, a large city cannot obtain enough water from local and regional sources to supply needs even with reductions in consumption.

To sift through possible operational states, water management practice could develop analytical approaches that define system states, *s*, by a collection of system characteristics, c, each with discrete values:

$$s(c_1, c_2 \dots c_n) \qquad (13)$$

Each state would constitute a point in an *n*-dimensional space, which provides a mechanism for comparing two points. Figure 6 shows several possible 3-dimensional graphs of possible operational states. The distance can be calculated in *n*-dimensions and augmented by measures that integrate the possibility of thresholds or other relationships between two points.

Figure 6: Three-dimensional *state graphs* combining different system characteristics to compare options across axes. Graphing transitions in system states can identify thresholds. Further dimensionality can be added through a variety of visualization techniques, including color and size.



This analysis approach is most practical for considering 3-dimensions (*x,y,z*) of factors that define a system state. For instance, graphing total cost, water quality, and management structure would reveal multi-dimensional relationships and potential non-linear effects. Beyond 3 axes, other graphical techniques can use color, space, and size to display more dimensions. Additionally, analytical techniques such as dimensional analysis or principal components analysis can reduce dimensionality. Dynamic computer visualizations lend well to communicating results to policymakers. In water resources, software that integrates genetic algorithms and visualizations has been used to address multi-objective and many-objective (greater than four objectives) problems for management of water distribution systems, groundwater, and other systems planning applications (Reed et al. 2003, 2013; Fu et al. 2013; Kasprzyk et al. 2013). Single-objective optimization may be too simplistic to identify long-term solutions for multi-objective problems involving uncertainty and a range of competing resources and stakeholder objectives (Brill et al. 1990; Reed & Kasprzyk 2009).

6 Conclusions

The concept of ecological resilience is applied to the management of a water resources network. Resilience has become a widely-used heuristic that signifies how managers address uncertainty and the need for stability in infrastructure, economic, and environmental systems. In water management, resilience typically emphasizes stability, so-called engineering resilience, to promote certainty of resource availability. Emerging perspectives that consider complexity and links between social and ecological systems offer new frameworks for understanding infrastructure management. Ecological resilience recognizes many possible system states and considers factors that promote stability or change of potential configurations.

A simple network model, including water sources, infrastructure links, and users was created to understand persistence, change, and disturbances in water systems. Results of an optimization for cost-effective water supply allocations revealed relative stability in the configuration of supply across several important system changes, including the absence of existing infrastructure, the presence of subsidized alternatives, and reductions in conveyance supplies. Only large disruptions in conveyance imports yielded wider adoption of alternative sources and a “reorganization” of the network of supplies for cities. Model results reveal how large-scale infrastructure breeds path dependence and stability.

The analysis is subject to several limitations. First, while based on California’s water system, the model is hypothetical and has limited applicability to real-world complexity. Second, the model does not incorporate interactions and feedbacks between water, energy, and other sectors of linked human and environmental systems. Third, the sensitivity analysis included only supply reductions. Changes in subsidies or technologies could alter results. Demonstrating the value of ecological resilience for water resources management requires more robust analysis across systems of varying geography, climate, technology, and resource consumption.

Big changes to large systems are long-term efforts. These changes likely come from a combination of sudden large-scale disruptions, such as natural disasters or drastically new policies, and incremental changes, such as reduced availability of supplies, newly affordable technologies, and additional needs for environmental restoration. The uncertainty of climate variability in the next century introduces additional challenges, whereby water planners must consider how to build future systems in the absence of ready new supplies or relative certainty of annual rainfall distributions. This chapter helps to explain why resilience is fashionable in policy discussions and presents a conceptual framework to inform planning decisions for future management of water infrastructure networks.

7 References

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Chapter 6

Connectivity, Resilience, and Complexity in California Water Infrastructure

> *It is only in the very simplest instances that it can be shown briefly and without any technical apparatus how the independent actions of individuals will produce an order which is no part of their intentions; and in those instances the explanation is usually so obvious that we never stop to examine the type of argument which leads us to it.*
>
> - Frederick von Hayek, in The Counter-Revolution of Science (1955)

Abstract

Connectivity is central to the structure and function of systems. Connections between components of a water distribution system determine flow patterns and operational flexibility. Typical visualization techniques for water resource networks include schematics and geospatial overlays. Network analysis and visualization methods can provide new tools to assess and view connectivity in networks. This chapter presents an analysis of the structure and function of the California statewide water infrastructure network as modeled in CALVIN using network theory visualizations and metrics. It identifies important nodes and links in the whole network, as well as in the San Francisco Bay Area sub-network, using measures of centrality. It also assesses network-wide centralization and connectivity using measures of spacing, linkage, and central dominance. The network shows *small world* properties with clustered groups of nodes. Finally, the chapter analyzes the effects of network degradation through piecewise and cumulative removal of important components, revealing complex relationships between connectivity, efficiency, and central dominance. Results improve our understanding of the growth and structure of California water systems. They also provide new approaches to understand resilience in water resource networks.

1 Introduction

Water resource systems are connected networks of lakes, rivers, canals, aqueducts, pipes, and other natural or man-made components. These networks supply water, sometimes over long distances, to fulfill a variety of human needs. Over decades, California developed a statewide system of water distribution to support the state's diverse economy, combining local, state, and federal support to connect sources in the northern and eastern parts of the state with users in the central and coastal areas. The current system fulfills statewide demands across residential, commercial, industrial, and agricultural sectors by augmenting local supplies (regional surface and groundwater sources) with statewide conveyance. Existing systems and emerging management practices must adapt to meet projected water demands with potentially uncertain supplies. In past eras, water managers solved supply challenges by acquiring new sources, but today they seek flexibility to move water and manage demands, which can mitigate potential water shortages. Managers emphasize *portfolios* of potential source and demand management options, which may include water transfer agreements, groundwater and conjunctive use, water conservation, and more (Hanak et al. 2011). Such goals, which seek to maintain stable supplies in uncertain conditions, are captured by discussions of *resilience*. Increased structural and institutional connectivity may facilitate greater flexibility for managers to deal with shortages.

This chapter explores connectivity in California's state and regional water systems using network analysis approaches. It illustrates the use of visualizations and metrics from network theory to analyze complex water systems, and proposes how such metrics may be useful to assess system degradation, decentralization, and resilience. The chapter concludes with a discussion of the relevance of network analysis approaches in water resources and areas for future research.

1.1 Connectivity and Resilience

Stability, disturbance, and recovery are persistent themes in analyzing systems of many types. In ecology literature, *resilience* describes the ability of a system "to absorb changes of state variables, driving variables, and parameters, and still persist," while *stability* is "the ability of a system to return to an equilibrium state after a temporary disturbance" (Holling 1973). Connectivity among system components is intuitively important in many types of systems, but for ecosystems, *ecological resilience* is linked with "diverse, but overlapping, function within a scale and by apparently redundant species that operate at different scales" (Peterson et al. 1998; Gunderson & Holling 2002). While empirical testing of this concept within ecosystems is on-going (Sundstrom et al. 2012; Hensel & Silliman 2013), understanding the role of connectivity to maintain function in many types of engineered systems may improve their performance. Intuitively, within civil infrastructure and water resources, connectivity that promotes structural and functional diversity throughout a system can enhance operations. Yet, connectivity and redundancy are also expensive. Managers improve flexibility with greater connectivity, but such designs must also consider tradeoffs in cost and operation.

2 Bridging Connectivity and Resilience: Network Theory

The design and function of many built systems is inspired by natural structures and models (Benyus 2002). Infrastructure systems analysis can draw on ecological systems concepts to better characterize how connectivity promotes reliability and resilience. For water resource systems, the intuitive role of inter-network connectivity to encourage flexibility is recognized, but not well characterized. To date, most studies of connectivity in regional and large-scale water resource systems emphasize major pipelines and links, without utilizing more comprehensive methods. Developing tools to assess connectivity in water infrastructure networks can improve managerial capabilities to address uncertainty from human actions, component failures, and climatic events.

Network theory characterizes connectivity in spatial networks across many fields, including computer science, transportation, social network analysis, geography, urban planning, and ecosystems (Kansky 1963; Haggett & Chorley 1969; Alexander 1979; Rodríguez-Iturbe & Rinaldo 2001; Barthélemy 2011). These techniques are increasingly applied to study a variety of technological, biological, social, and information networks. Klau and Weiskircher (2005) describe a connected system as one where "there exists a path between every pair of vertices in the network," and provide a review of several useful system connectivity approaches. Network theory is a common approach to analyze some types of complex systems, which are systems that show unexpected properties that emerge from interactions of individual system components. Common analysis indicators examine network characteristics at multiple scales:

1) *Basic measures of network size* such as number of nodes and links;
2) *Network-level indices* use different statistical calculations to help characterize network properties, such as the link-to-node ratio for a network; and
3) *Link-level indices* describe the importance of particular nodes and links by measuring the number of connections between nodes as well as node clustering.

Some network-level indices compare networks of similar sizes based solely on the number of nodes and links. Other indices, such as characteristic path length, clustering coefficient, and measures of centrality, were developed to compare networks of different sizes (Freeman 1977). Different measures are often referred to by different names across fields. Table 1 summarizes important measures and the Appendix gives a more complete list of metrics. In equations of Table 1, e is the number of links (connections, arcs, or edges), v is the number of nodes (vertices or intersections), and p is the number of graphs or subgraphs, which in networks are a set of points in the same plane (Kansky 1963).

Network analysis and graph theory approaches have been used to study aspects of structure and reliability in water systems operations. Link-node descriptions of network topology and connectivity matrices are widely used in water resources modeling. Simulation and optimization incorporate parameters such as flow quantity and direction, pressure, and cost. Following component failures in a distribution system, redundancy and flow capacity of remaining components, which includes determining if demand nodes are connected to sources, dictate a system's ability to maintain deliveries (Wagner et al. 1988; Ostfeld & Shamir 1996). Water quality issues are especially relevant for networks that supply consumptive end-uses, as contamination depends on the magnitude and direction of flow, the virulence of constituents, and the network structure (Davidson & Bouchart 2003). Limited studies using network theory metrics, including measures of centrality and dispersion, have assessed aspects of network performance in theoretical and real-world municipal water distribution systems (Yazdani & Jeffrey 2010; Barthélemy 2011; Pandit & Cittendon 2012). Networks with dispersed storage sites may show greater resistance to failure from targeted attacks (Albert et al. 2000; Pandit & Cittendon 2012). Network-based approaches for designing water systems can incorporate monitoring and control technologies, identify hierarchical source and demand relationships, and delineate functional sub-sectors that promote reliability during outages (Di Nardo et al. 2014).

2.1 Small world and scale-free networks

Some networks have been characterized as *small worlds*. Small world networks are highly clustered and have short distances between nodes, where all adjacent nodes separated by a distance of 1 (Watts & Strogatz 1998; Montoya & Solé 2002). Small-world networks can be identified by two values: *average path length* and *clustering coefficient*. The average path length, which characterizes efficiency, measures separation of nodes throughout the network and is the average of the shortest distances between two nodes for all nodes (Latora & Marchiori 2001). Larger path lengths indicate a more dispersed network. The clustering coefficient measures the average fraction of pairs of neighbors to a node (nodes it is directly connected to) that are also neighbors of each other (Watts & Strogatz 1998):

$$C_i = \frac{1}{n}\sum_{i \neq j}\frac{v_i}{k_n(k_n - 1)} \tag{1}$$

In Equation 1, v_i is the number of connected links to the neighbors of node *i,* and k_n is the number of neighbors of *i*. In other words, it is the ratio of the number of edges between node *i* and its neighbors to the maximum number of edges between node *i* and its neighbors. Higher average clustering coefficients indicate more clustered networks.

Small-world networks have small *path lengths* and greater *clustering coefficients*. These values can be compared to randomized networks, or networks of the same nodes that have a random distribution of connections. Small-world networks have significantly larger clustering coefficients than in randomized networks. The path lengths of random networks, however, are also small. The average path length of a small-world network may be either more or less than the equivalent randomized network without affecting the network's characterization as small-world (Albert & Barabási 2002; Montoya & Solé 2002).

Another related class of networks, *scale-free* networks*,* can be a subset of small-world networks (Barabási & Albert 1999). Scale-free networks have small world properties, but in addition, have no constraints on the number of connections to any one node. In other words, of all the nodes in the network, most may have 1, 2, or 3 connections, but some small number of preferential nodes will have many connections and the number of these connections is not constrained. Alternatively, scale-limited networks have a similar number of nodes with fewer connections, but at some limit, preferential nodes cannot absorb more connections. For example, in a high school social network, if a popular (preferential) student had unlimited time to interact with all other students interested in connecting, then that person would contribute to the network being scale-free. Only a few preferential nodes are necessary to make the network scale-free.

Table 1: Selected network analysis metrics, separated by measures of the entire network, a single node, or a single link

Indicator	Description	Interpretation	Symbol	Formula
<u>Assessing Network-Wide Connectivity</u>: Network-Level Metrics				
Alpha Index (Meshedness coefficient)	Ratio of the # of loops in a network (nodes continuously connected from “A” to “A”) to the maximum possible # of loops (Kansky 1963; Buhl et al. 2006; Yazdani & Jeffrey 2011)	Higher alpha values indicate more connected networks	α (r_m)	$\frac{e-v}{2v-5}$ * $e-v$ *for a multi-source network*
Beta Index	Ratio of the number of links (edges) to nodes (vertices) in the network (Kansky 1963)	Higher beta values indicate more complex networks	β	$\frac{e}{v}$
Gamma Index (Link Density)	Ratio of the number of observed links and the number of possible links in a network (Kansky 1963)	A value between 0 and 1, where 1 is a completely connected network	γ	$\frac{e}{3(v-2)}$
Characteristic Path Length	Average of the shortest path-lengths in a graph, where i and j are two nodes (Albert & Barabási 2002)	Shorter path lengths indicate more efficient networks	L	$L=\frac{1}{v(v-1)}\sum_{i\neq j} d_{ij}$ *Where d_{ij} is the distance between nodes i and j*
Central-Point Dominance	Average difference in node centrality of the most central point and all others	Higher in centralized networks and lower in localized networks	C_b	$C_b=\frac{\sum_{i=1}^{n}[C_b(k_{cent})-C_b(k_i))]}{n-1}$
<u>Identifying Important Nodes</u>: Node-Level Measures				
Node Centrality (Betweenness Centrality)	# of shortest paths between two points that pass through a node divided by the total # of shortest paths between two points (Freeman 1977).	Higher node centrality indicates a node is more critical to network structure	$C_b(k)$	$C_b(k)=\sum_{i\neq j\neq k}\frac{g_{ij}(k)}{g_{ij}}$ *Where g is the number of shortest paths and g(k) are shortest paths passing through k*
<u>Identifying Important Links</u>: Link-Level Measures				
Link Centrality (Link/Edge Betweenness)	The # of shortest paths between two nodes *i* and *j* that go through an edge, divided by the total # of shortest paths that go from *i* to *j* (Newman & Girvan 2004; Assenov et al. 2007).	Higher link centrality indicates a node is more critical to network structure	B_e	$B_e(k)=\sum_{i\neq j\neq k}\frac{h_{ij}(k)}{h_{ij}}$ *Where h is the # of shortest paths between two nodes and h(k) are shortest paths through link k*

<u>Definitions</u>: e = # of links; v = # of nodes; p = # of sub-graphs (independent graphs that can be generated within the entire graph)

Scale-free and scale-limited networks have been characterized according to their distribution of node degrees (the number of connections per node). In scale-free networks, the distribution of links to node *k* follows a power law:

$$P(k) = ck^{-\alpha} \tag{2}$$

Scale-free networks are argued to emerge from the preferential connection of new nodes to existing, well-connected nodes. This reinforces highly-connected nodes.

Research has explored how some technological, social, and environmental networks, including urban populations, World Wide Web hyperlinks, and scientific citations, exhibit such properties in regions of their node degree distribution (Albert and Barabási 2002; Bettencourt et al. 2007; Clauset, Shalizi, and Newman 2009). A linear distribution of data on a log-log plot, approximated by a line of best fit following Equation 2 with a slope (α), is a common identifier of scale-free network properties. Determining the line of best fit using a least-squares linear regression of logarithmic, non-zero values dates back to Pareto's analysis of wealth distribution (Arnold 1983). In literature, many scale-free networks have reported α values between 2.1 and 4, depending upon the type of network (Barabási and Albert 1999), though some networks have α values of less than 2 (Montoya and Solé 2002). Of high relevance for this analysis, scale-free networks may have important characteristics for operations, vulnerability, and resilience. Albert et al (2000) found that while scale-free networks are resistant to randomized failures, they are vulnerable to targeted failures of central nodes.

Yet, scale-free networks are not universal and they are easily misidentified (Amaral et al. 2000; Clauset, Shalizi, and Newman 2009). Skewed and power law distributions are common in many types of systems and may not necessarily indicate universal properties (Simon 1955; Fox Keller 2005; Mandelbrot 1960). Moreover, apparent power-law trends can dissipate upon further inspection (Shalizi 2011). Many reported scale-free networks use a line of best fit derived from a least-squares regression, but such procedures can produce known misrepresentations. Appropriate statistical tests beyond least-squares regression can confirm how well a power law or other distribution represents data (Amaral et al. 2000; Clauset, Shalizi, and Newman 2009). Better procedures use the *method of maximum likelihood* to determine the Maximum Likelihood Estimator (MLE) of the scaling parameter (α) along with the Kolmogorov-Smirnov (KS) statistic to identify the lower bound of the region approximated by a power law distribution. Most data sets, whether continuous or discrete, are well-approximated by power law distributions only in particular regions of the distribution (Clauset, Shalizi, and Newman 2009).

For a continuous distribution, the MLE is equal to:

$$\hat{\alpha} = 1 + n\left[\sum_{i=1}^{n} \ln\frac{k_i}{k_{min}}\right] \tag{3}$$

where $\hat{\alpha}$ is the alpha derived from empirical values, k_i are the observed values of the node degree distribution, and k_{min} is the minimum value of k. Statistical significance (goodness-of-fit) for the distribution can be determined using the *p-value* and comparing it to other generated data sets or approximated distributions. Further, the value of the scaling parameter must be estimated only for the valid region with a lower bound, k_{min}, which may be identified using several procedures. I use the KS statistic, D, which determines the maximum distance between the distribution of empirical data $(S(x))$ greater than k_{min} and a fitted model of the distribution $(P(x))$:

$$D = max_{k \geq k_{min}} |S(k) - P(k)| \tag{4}$$

The estimate of the lower bound of the distribution of empirical data that follows the fitted model minimizes the KS statistic. In other words, the best estimate of k_{min} in the empirical distribution minimizes D for the region remaining in $k \geq k_{min}$.

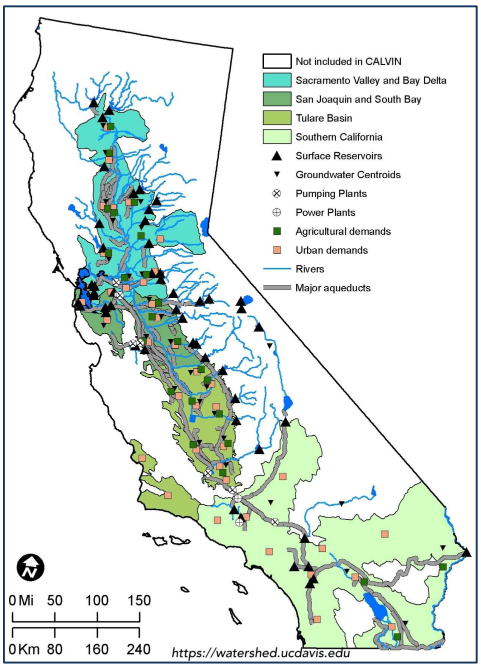
In combination, these two procedures are the basis for better procedures to determine regions of the distribution that are well-approximated by power laws and the corresponding scaling parameters. Subsequently, a goodness-of-fit determines if the power law distribution (or any other distribution) is a good fit using a p-value. Importantly, however, all statistical procedures rule out rather than confirm a hypothesis, so cautious conclusions regarding approximations are prudent.

For a directed network where flows can only move in one direction, the distribution of node degrees can be calculated for *in-degree* (connections flowing into a node) and *out-degree* (connections flowing out of a node) values. Many scale-free networks have typical α values between 2.1 and 4, depending upon the type of network (Barabási & Albert 1999), while some networks such as citation links or small food webs have α values of less than 2 (Montoya & Solé 2002).

Characteristics of scale-free networks may have important considerations for operations, vulnerability, and resilience in networked systems. Albert, Barabási and Jeong (2000) found that while scale-free networks are resistant to randomized failures due to their connectivity, they are vulnerable to targeted failures of central nodes. In the context of critical infrastructure protection or computer security, targeted failures occur from attacks and address notions of resilience in engineering and policy.

3 Analyzing Connectivity in the California Water Network

Figure 1: California water infrastructure in CALVIN (source: UC Davis)



Results from a network analysis for the California water distribution system are divided into sub-sections that describe major insights and associated calculations. Network-level indices analyze connectivity in the full water distribution network. While some research has developed methods for designing water distribution networks that minimize costs while maintaining or maximizing reliability across a network (Gupta & Bhave 1994; Martínez 2010), network analysis metrics can analyze structural characteristics more broadly. Rather than consider the reliability of individual elements, network theory approaches understand performance and connectivity by analyzing linkages between nodes in a network of infrastructure elements (Yazdani & Jeffrey 2010; Barthélemy 2011; Pandit & Cittendon 2012).

California has a highly-managed, statewide water management network designed for variable hydrologic conditions. Water is conveyed through infrastructure and natural channels from northern and western regions to agricultural and urban users in central and southern regions Figure 1. In the center, the California Delta serves as the hub of statewide conveyance. Large state and federal water projects combine with local and regional infrastructure to convey, store, and distribute water for urban, agricultural, and environmental uses. This connectivity was built over decades.

CALVIN is an economic-engineering model developed at the University of California, Davis, which optimizes water storage and transport throughout California. The model, illustrated in Figure 1, uses a link-node structure to define relationships between system components and a 72-year monthly time series of hydrology represents system variability.

CALVIN analyses have assessed regional and statewide planning issues, including integrated water management, water markets, conjunctive use, climate change, environmental remediation, and others (Draper et al. 2003; Tanaka & Lund 2003; Jenkins et al. 2004; Null & Lund 2006; Tanaka et al. 2006; Medellín-Azuara et al. 2007). The CALVIN network includes 858 spatial nodes and 1,368 links. Links are assigned attributes such as capacity, cost of operations, and penalties for failing to meet flow targets. The link-node structure of CALVIN lends to network analysis.

To conduct a network analysis, the CALVIN network was imported into the open-source network analysis software *Cytoscape*. Originally developed for biomedical research applications, *Cytoscape* can describe, analyze, and visualize many types of networks. It also includes packages for calculating common network analysis metrics. The *NetworkAnalyzer v.2.7* plug-in for *Cytoscape* calculates statistics for links, nodes and the entire network (Assenov et al. 2007). Common metrics were calculated for the entire CALVIN network and the San Francisco Bay Area sub-network. In addition, different graphing and visualization algorithms were used to identify critical infrastructure and trends in connectivity. A summary of results follows.

3.1 *Small world* and *scale-free* properties in the CALVIN network

I calculated network analysis metrics and the node degree distribution for versions of the CALVIN network with and without calibration nodes (Table 2). While the full network has 858 nodes, removing calibration nodes that assist in mass conservation calculations reduces the network size to 596 nodes. The network metrics indicated small-world properties. The *clustering coefficient* of the CALVIN network was significantly higher (.066) than the same metric in the randomized CALVIN network (2.3 x 10^{-4}). The *path length* of the actual CALVIN network (22.46) was much larger than the randomized network (10.42). In the reduced network without calibration nodes, the *clustering coefficient* of the CALVIN network is higher (0.093) than the same metric in the randomized CALVIN network (0.005). The *path length* of the reduced CALVIN network (26.03) is also larger than the randomized network (11.03). The small world parameters of the CALVIN network are similar to values reported for the Southern California power grid (Watts & Strogatz 1998). Yet, this power grid network was not scale-free, as its node degree distribution followed an exponential rather than a power law function (Amaral et al. 2000; Strogatz 2001). Similarly, other infrastructure networks, such as pipe networks in cities, have not shown consistent power law relationships.

Scale-free networks have node degree distributions that follow a power law (Equation 2). In undirected networks (flows move both ways), the node degrees are characterized by a single distribution. In directed networks (flows move one way) such as CALVIN, however, node degree distributions may be either *in-degree* or *out-degree*. Node degree distributions for *in-degree* (connections flowing into a node) and *out-degree* (connections flowing out of a node) values were calculated for the entire directed CALVIN network (858 nodes) using the *NetworkAnalyzer v.2.7* tool in *Cytoscape*. I exported the statistics for analysis using the *powerlaw* package in the *IPython QT Console* (Continuum Analytics 2014; Alstott, Bullmore, and Plenz 2014). To analyze *scale-free* properties in the CALVIN network, I followed network science literature and procedures described by Clauset et al (2009). The node degree distribution in CALVIN is a discrete set of values, such that:

$$p(k) = \Pr(K = k) = ck^{-\alpha} \quad (5)$$

where K is the observed value of the node degree. MLEs can be derived for either continuous or discrete parameters, so identifying the node degree distribution of integer values determines the specific implementation of the MLE (Clauset, Shalizi, and Newman 2009). I tested the validity of a power law approximation for the data using: 1) a least-squares linear regression of logarithmic, non-zero values, and 2) Maximum Likelihood Estimators (MLEs) of discrete integer values for the node degree in combination with a Kolmorgorov-Smirnov (KS) statistic.

Using the least-squares regression for node degrees in the directed CALVIN network, the coefficient α values for the in-degree and out-degree distributions were *2.7* and *2.3*, with a high coefficient of determination for each line of best fit ($R^2 = 0.97$ and $R^2 = 0.90$, respectively). For the reduced network without calibration nodes, the coefficient α values for the in-degree and out-degree distributions using least-squares regression were *2.88* ($R^2 = 0.94$) and *3.55* ($R^2 = 0.91$). Thus, using least-squares regression over the entire empirical distribution, power laws are reasonable fits. Figure 2 shows the in- and out-degree distributions for nodes, along with the least-squares estimates of power law approximations and associated R^2 values, for both networks.

Table 2: Comparing *scale-free* and *small world* networks from literature to the CALVIN network. Some networks (power grid) are small world, while others (World Wide Web, Internet Routers) are both *small world* and *scale-free*. The CALVIN network exhibits small world properties, but after rigorous statistical testing, its node degree distribution is not well approximated by a power law distribution. (LSR: method using least-squares regression, MLE/KS: method using Maximum Likelihood Estimates and Kolmorgorov-Smirnov statistics).

Network	# of Nodes	α_{in}	α_{out}	L	L_{random}	C_i	C_{random}	Source
Power Grid	4,941	**	**	18.7	12.4	0.08	0.005	Watts and Strogatz (1998)
Food Webs (Silwood Park)	154	1.13	1.13	3.4	3.23	*	*	Montoya and Sole (2000)
World Wide Web	325,729	2.1	2.45	11.2	8.32	0.108	2.3e-4	(Albert, Barabási, and Jeong 1999)
Internet Routers	3,888	2.48	2.48	12.15	8.75	*	*	(Faloutsos, Faloutsos, and Faloutsos 1999)
Movie Actors	212,250	2.3	2.3	4.54	4.65	*	*	Barabasi and Albert (1999)
Metabolic (E. coli)	778	2.2	2.2	3.2	3.32	*	*	(Jeong et al. 2000)
CALVIN (LSR)	**858**	**2.7**	**2.3**	**22.46**	**10.42**	**0.066**	**0.002**	
CALVIN (LSR)	**596**	**2.9**	**3.6**	**26.03**	**11.03**	**0.093**	**0.005**	
CALVIN (MLE/KS)	**596**	**3.1***	**4.7***	**26.03**	**11.03**	**0.093**	**0.005**	

* only over a portion of the node degree distribution
** not reported

Using MLEs and KS statistics, however, the goodness of fit for a power law approximation dissipates. The regions of fit identified by the KS statistic limited the in-degree distribution to values of $k \geq 2$ (162 nodes) and the out-degree distribution to values of $k \geq 3$ (188 nodes). The remaining valid regions become quite small to compute valid statistics. Using the *powerlaw* package, I plotted the empirical values of the remaining valid region of each node degree distribution against estimates of the power law, lognormal, and exponential distributions, as shown in Figure 3. Visual inspection shows that the power law distributions are not good approximations of the decaying upper tails of both in-degree and out-degree distributions. Further statistical indicators such as the loglikelihood ratio are useful to compare potentially explanatory distributions, but given the small number of observations greater than k_{min} and the results of the visual inspection, the power law distribution does not explain the distribution of node degrees for either case.

Figure 2: In-degree (left) and Out-degree (right) distributions of node degree values for: A) (top) the full CALVIN network (858 nodes) using Least-Squares Regression, B) (bottom) the reduced CALVIN network (596 nodes) without calibration nodes using Least-Squares Regression, Node degree is the value of the number of connections to a node. In directed networks (flows move one way), node degree distributions are calculated for nodes based on connections coming in (in-degree) and connections flowing out (out-degree). In undirected networks, only one node degree distribution exists.

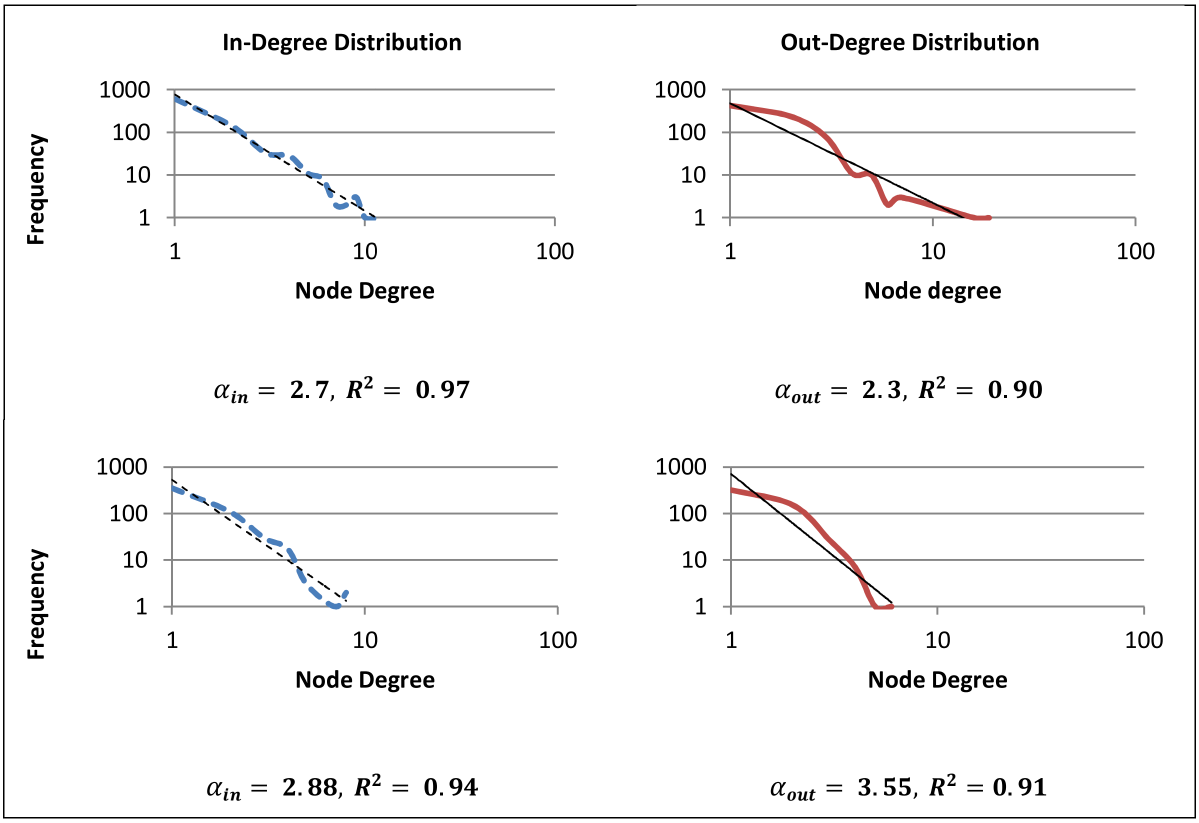
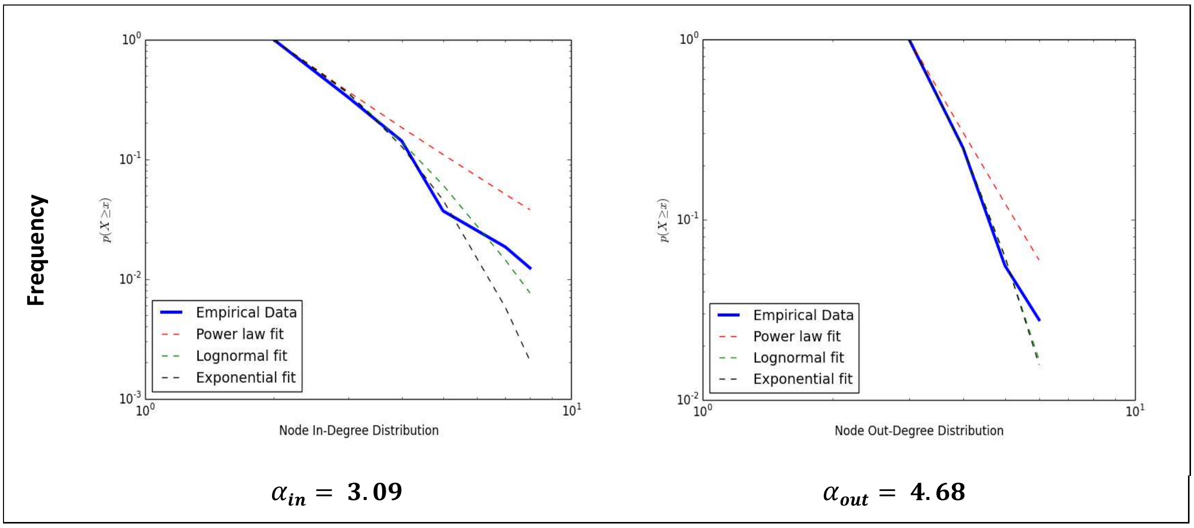


Figure 3: Visual inspection of the goodness-of-fit for power law, lognormal, and exponential distributions for the reduced CALVIN network (596 nodes). Maximum Likelihood Estimators determine scaling parameters and Kolmorgorov-Smirnov statistic identifies regions of fit. Power law distributions do not fit the data well. Using the KS statistic, the minimum value of *k* for the in-degree distribution is equal to 2, while the minimum value of *k* for the out-degree distribution is 3.



Finally, I assessed the relevance of preferential nodes, which have a high node degree value. The most preferential nodes, which are listed in Table 3, include inflows to Sacramento, Santa Clara, and East Bay Municipal Utility District (EBMUD) municipal systems, Central Valley groundwater basins, the Salton Sea, and the Coachella canal. Many of the nodes are in the central part of the state. For municipalities, the high node degree indicates systems that draw on many sources. The preferential nodes identified, however, are not dominant infrastructure components such as the California Aqueduct, which one would hypothesize to be preferential. Instead, preferential nodes tend to be municipal or agricultural components.

Table 3: The most preferential nodes in the CALVIN network (not including calibration nodes).

Node Degree	# of Nodes	Node Names
7	6	Coachella Canal and groundwater basin; State Water Project delivery node for Central Valley; Central Valley groundwater basins
8	2	EBMUD Inflows; New Don Pedro Reservoir
9	2	Central Valley groundwater basins
10	1	Sacramento Municipal inflows
11	1	Santa Clara Valley urban inflows

3.2 Bifurcated networks structure: Northern and Southern California

Northern and Southern California regional water systems are distinct. A visualization algorithm was used to develop circular representations of network structure based on connectivity, as shown in Figure 4, with nodes grouped roughly by geography and clusters listed in Table 4. The division between northern and southern networks is evident, with the California Aqueduct serving as a critical connection. Figure 5 & 6 as well as Table 5 all highlight connectivity between identified regions throughout the circle in more detail.

Inter-regional connectivity varies, as indicated by the densities of lines between points around the circle. For instance, the San Francisco Bay Area is well-connected to Sacramento and Folsom nodes, though it is not well connected to nodes in the Friant-Kern Canal and southern Central Valley regions. While visualization can illuminate or reinforce understanding of system characteristics, it may also obscure important characteristics. For instance, Figure 4 does not indicate directionality of flows between regions. Simple visualization algorithms are probably most informative for experienced practitioners familiar with the network, while analysis using additional weightings, groupings, color schemes, or other symbols can be useful to package information for unfamiliar parties.

Figure 4: California water network visualization showing connectivity of node clusters in system. Links (in blue) connect two nodes (arranged around the circle). Areas of heavy blue indicate greater connectivity. The Northern and Southern networks are highly regionalized and connected primarily through the California Aqueduct. Nodes and links for each cluster are identified in Table 4 (SWP: State Water Project; CVP: Central Valley Project).

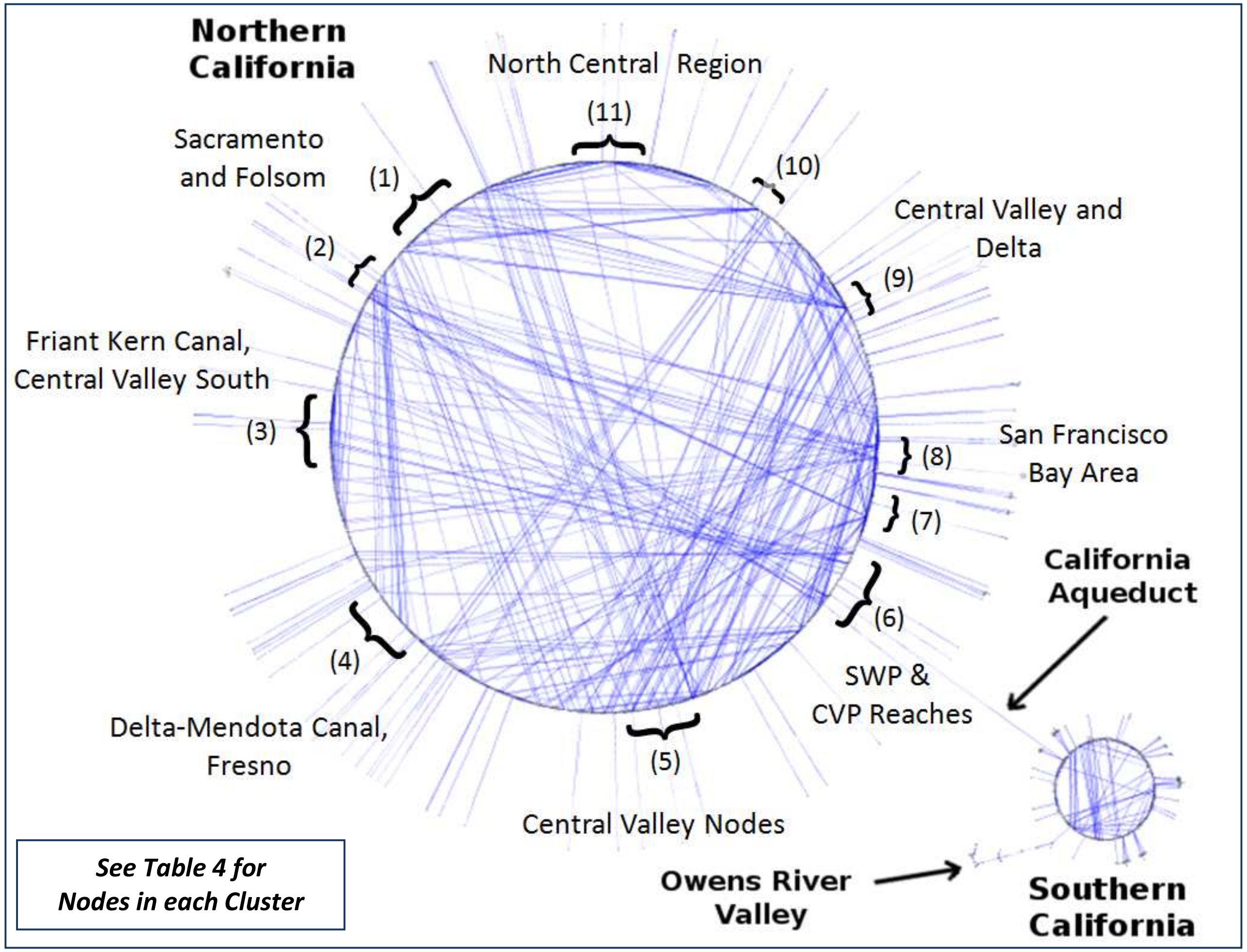


Table 4: Nodes and Links included in clusters labeled in Figure 4 (CVPM: Central Valley Project Model)

Cluster Label	Nodes
(1)	**Sacramento and Folsom:** Sacramento River inflows and diversions; American River inflows and diversions; Walnut Creek Pumping Plant; Cosumnes River diversions; Placerville and Auburn demands
(2)	**Central Valley Storage and Conveyance:** San Luis Reservoir; Millteron Lake; Friant-Kern Canal; Central Valley Project (CVP) Deliveries, Central Valley Urban Demands (CVPM Region 8); Pacaheco Tunnel to South Bay; Delta-Mendota Canal Diversions
(3)	**Central Valley Rivers and Conveyance:** Friant-Kern Canal; Kern River; Tule River
(4)	**Central Valley Conveyance, Storage, and Pumping:** Los Banos Creek Reservoir; Delta-Mendota Canal nodes; O'Neill Pumping Plant; Gianelli Pumping Plant;
(5)	**Central Valley Urban Diversions and Flood Control:** Central Valley urban diversions (CVPM Regions 2, 3, 9); Yolo Bypass inflows; Knight's Landing; Putah Creek outflows to Yolo Bypass
(6)	**Central Valley Conveyance Infrastructure and Rivers:** San Joaquin River diversions; King's River; Pine Flat Reservoir; Edmonston Pumping Plant; Central Valley Urban Demands (CVP 5)
(7)	**Central, Southern, and Eastern San Francisco Bay Area:** San Francisco Public Utilities Commission (SFPUC) inflows and outflows; Santa Clara (southern Bay Area) inflows and outflows; East Bay Municipal Utility District (EBMUD) inflows and outflows
(8)	**San Francisco Bay Area Inputs:** Mokelumne River Aqueduct; Mallard Sough; Contra Costa
(9)	**Eastern Central Valley, Delta, and Northern Bay Area:** Napa Valley inflows and outflows; Solano demands and flows ; Central Valley urban demands (CVP 2); Cache Creek flows; Clear Lake
(10)	**Sacramento County Demands:** Sacramento inflows
(11)	**Northern California Storage and Conveyance:** Shasta Dam and Reservoir; Trinity River; Central Valley urban demands (CVPM Region 5); Colusa Basin drain; Whiskeytown Lake

Figure 5 : California water network visualization identifying clusters of links connecting two regions. <u>Nodes (numbered) and links (lettered) in each cluster are identified in Table 5</u> (SWP: State Water Project; CVP: Central Valley Project).

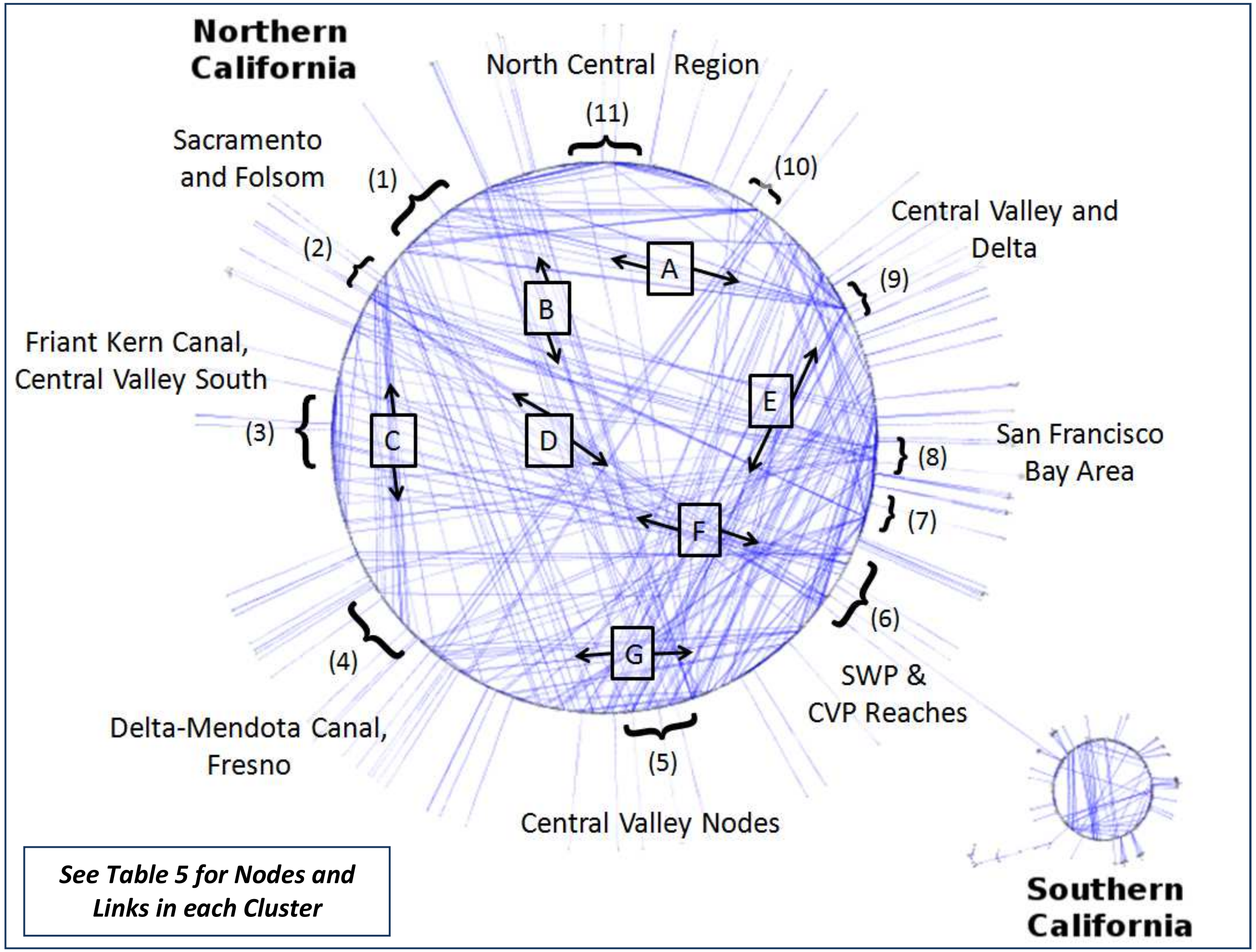
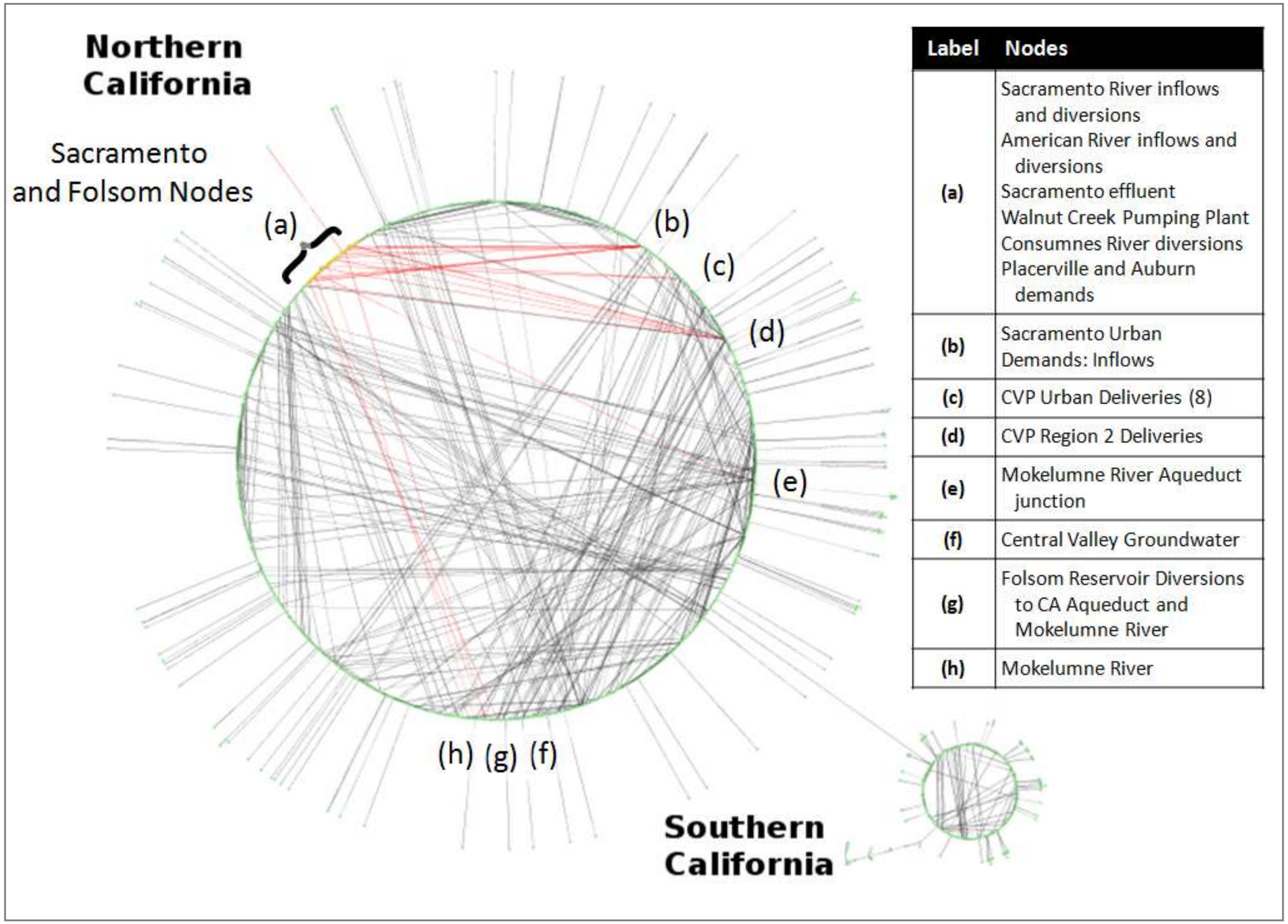


Table 5: Links included in clusters labeled in Figure 5
(SWP: State Water Project; CVP: Central Valley Project; CVPM: Central Valley Project Model)

Cluster Label	Links
(A)	**Sacramento to Central Valley & Delta:** Inflows/Outflows to Mokelumne storage; American River diversions; Cosumnes River Inflows; Feather River outflows;
(B)	**North-Central Region to Central Valley:** Sacramento River diversion to CVP Region 2; Sacramento River diversions (between Red Bluff and Ord Ferry); Tehama-Colusa Canal deliveries to CVPM Region 2; Glenn-Colusa Canal & Tehama-Colusa Canal deliveries to CVPM Region 3; Sacramento River diversions (between Knight's Landing and Sacramento); Yolo Bypass; Sacramento River diversion to Glenn Colusa Canal
(C)	**Sacramento to Delta-Mendota Canal/Fresno:** Gianelli Pumping Plant releases; O'Neill Pumping Plant releases; San Luis Reservoir Releases; Delta-Mendota Canal; California Aqueduct reaches
(D)	**Sacramento/Friant-Kern to SWP/CWP Reaches:** King's River; Friant-Kern Canal discharge to King's River; San Joaquin River reach (between Friant Dam and Gravelly Ford Reach); Friant-Kern Canal diversion to Fresno
(E)	**Connections within the Central Valley & Delta:** Putah South Canal delivery to CVPM Region 6; Stockton outflows and discharges; Sacramento River diversion to North Bay Aqueduct; Putah Creek inflow to Yolo Bypass
(F)	**Friant-Kern Canal & Central Valley South to SWP/CWP Reaches:** Kern River diversions to Buena Vista Lake; Bakersfield stormwater discharges to Kern River; California Aqueduct reaches
(G)	**Delta-Mendota Canal/Fresno to SWP/CWP Reaches:** San Joaquin River reach (between Gravelly Ford and Coachella Bypass); Groundwater pumping to CVPM Region 2; Chowchilla River diversions to CVPM Region 13; Mendota Pool to CVPM Region 13; Fresno River diversions to CVPM 13; San Joaquin River riparian diversions (Mendota Pool to CVPM 13);

Figure 6: CALVIN visualization with nodes and links highlighted (in red) for Sacramento and Folsom. Algorithms with interactive capabilities can help explore connectivity within complex systems

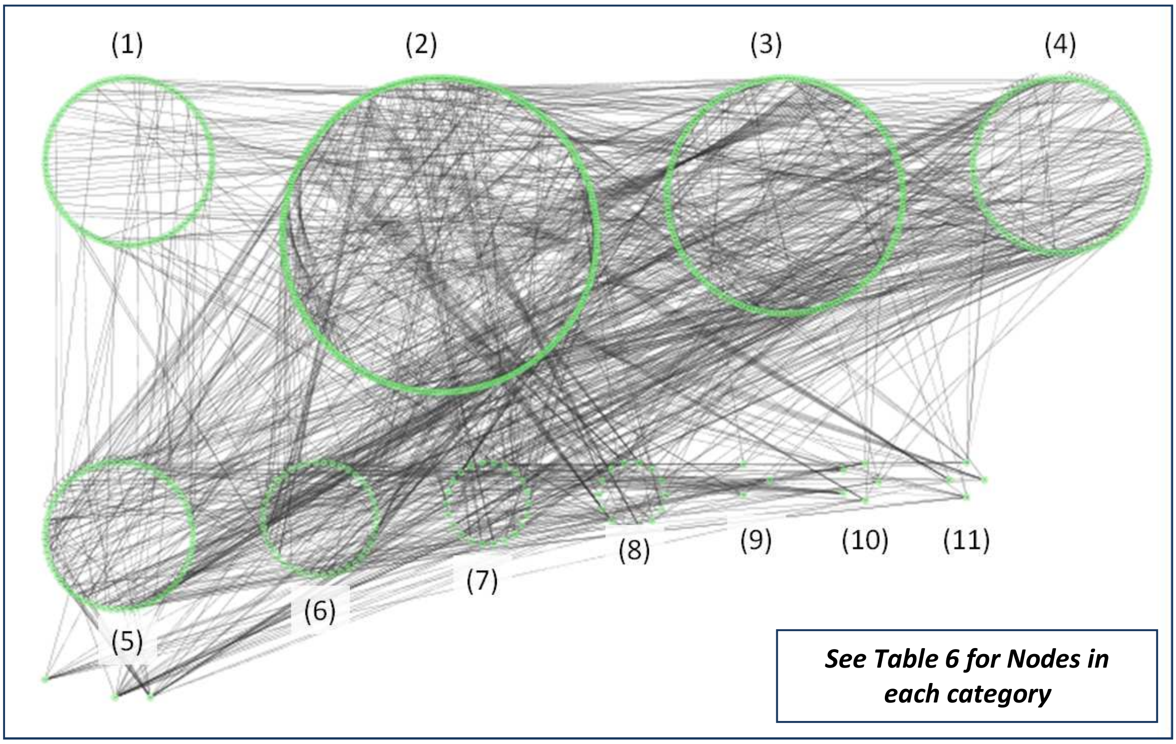


Label	Nodes
(a)	Sacramento River inflows and diversions American River inflows and diversions Sacramento effluent Walnut Creek Pumping Plant Consumnes River diversions Placerville and Auburn demands
(b)	Sacramento Urban Demands: Inflows
(c)	CVP Urban Deliveries (8)
(d)	CVP Region 2 Deliveries
(e)	Mokelumne River Aqueduct junction
(f)	Central Valley Groundwater
(g)	Folsom Reservoir Diversions to CA Aqueduct and Mokelumne River
(h)	Mokelumne River

3.3 Connections per node throughout the system

The node degree (number of links per node) distribution described above can be visualized in several ways, as shown in Figure 7. Across the modeled network, most nodes have 3 or fewer links. Many nodes with two connections (the largest circle in Figure 7) are intermediate hubs in the network, including calibration nodes and groundwater pumps. Nodes with three connections, however, include important parts of the statewide system such as the California Aqueduct. This is likely explained by two factors: upstream sources with one inflow and two outflows, or intermediate conveyance nodes that merge two inputs into one downstream channel.

Figure 7: CALVIN network nodes, grouped by the number of connections (inflows and outflows) for a node, as labeled. A large percentage of network nodes have 2 connections (one inflow and one outflow). More connections per node may improve flexibility for supplies, releases, and routing.



Some nodes have many connections. For instance, nodes with more than eight connections include inflows to meet urban demands for Sacramento, Santa Clara, and Eastern San Francisco Bay (East Bay Municipal Utility District) metropolitan systems. For Sacramento, this indicates diversified sources (surface and groundwater pumping) and its central position in the network for conveyance. For Santa Clara, the high link-node ratio indicates its diverse sources as well as its central role in distributing water to the South Bay and Silicon Valley areas. The Santa Clara Valley relies on many sources to meet demands, including the CVP, the San Francisco Public Utilities Commission, groundwater pumping, and local surface sources. Many agricultural and smaller urban nodes in the Central Valley Project system are also well-connected. Agricultural nodes in the Central Valley and Delta also serve as hubs for surface and groundwater.

Table 6: Example of nodes for each category of Connections per Node, as shown in Figure 7

Connections per Node	# of Nodes	Example Nodes
1	91	Sinks, outflows, and calibration nodes throughout system
2	322	Pumping plants (Tracy, Banks, etc); MWD reservoirs; California Aqueduct reaches
3	181	Owens Lake; California Aqueduct reaches; Coachella Canal and River; Coastal Aqueduct; MWD pipelines to San Diego; Wildlife reserves
4	100	Lake Berryessa; Friant-Kern Canal reaches; Eastman Lake; New Melones Reservoir; CVP Inputs (Regions 8,9,10,13,17); Hetch Hetchy Aqueduct; South Bay Aqueduct; California Aqueduct reaches; Mokelumne River Aqueduct
5	71	San Luis Reservoir; Lake Del Valle; Hetch Hetchy Reservoir; Keswick Reservoir; Clair Engle Lake; Lake Lloyd/Lake Eleanor; Bay Area urban outflows
6	42	Kaweah River; Los Angeles region urban inflows; Contra Costa urban inflows; Millerton Lake
7	22	Yolo Bypass inflows; Santa Clara Valley regional outflows; La Grange Dam; Mendota Pool; Salton Sea; Kern River
8	14	East Bay MUD Inflows;
9	3	New Don Pedro Reservoir
10	5	Tulare Lake inflows
11	4	Sacramento and Santa Clara Valley urban inflows

A diversity of supplies in the connected network should improve a location's ability to purchase water from more potential sources. At the same time, long-term vulnerability may result if a location has junior water rights and supplies decrease. While greater interconnectivity supports structural flexibility to manage climate and supply variability, the state's complex water rights structure can make areas with junior rights vulnerable during periods of decreased supply.

3.4 Central California components are important features

Of the over 800 nodes in the network, important nodes were assessed by an index of their scores on a composite of high rankings across many node-level metrics. All nodes in the network were ranked for each of nine metrics (as shown in Table above and in the Appendix).[1] Nodes were subsequently categorized based on the number of times they ranked in the top 30 of all nodes. Table 7 shows the top results of this composite index of node metrics. California Aqueduct connections are prevalent, as are large natural supplies and constructed conveyance. Many of the river segments and reservoirs are located in the Central Valley of California, which serves as a hub for water conveyance and storage in dams and channelized rivers.

[1] List of node centrality metrics include: *Average Shortest Path Length*, *Node Centrality*, *Clustering Coefficient*, *Degree*, *Neighborhood Connectivity*, *Number of Directed Edges*, *Radiality, and Topological Coefficient*

Table 7: CALVIN nodes ranked according to the number of times the node appears in the top 30 of all nodes across several metrics of criticality within the network. A composite of different indicators may more accurately identify important nodes. An expanded table appears in the Appendix.

Node Name	Type	# of Node Appearances in Top-30 of All Centrality Metrics[1]
California Aqueduct Deliveries: Friant-Kern & Fresno	Connection Node	5
Mendota Pool	Reservoir	5
New Don Pedro Reservoir	Reservoir	5
San Joaquin Riv. diversion: CVPM Region 10	Connection Node	4
Feather River inflow to Sacramento River	Natural Resource	4
La Grange Dam	Reservoir	4
California Aqueduct diversion to CVPM 10	Connection Node	3
Millerton Lake	Reservoir	3
Stanislaus River diversion	Connection Node	3
New Melones Reservoir	Reservoir	3
Lake McClure	Reservoir	3

Similarly, links can be ranked using link centrality, as shown in Table 8. Higher scores show links that are important for system operation. Many of the highly-ranked connections are Delta inflows, such as particular reaches of the San Joaquin River and sections of the Friant-Kern canal. In addition, reaches of the California Aqueduct in central California, especially near the split of the aqueduct into eastern and western branches, are prominent. Finally, diversions from the Central Valley Project in the Delta (Region 10) appear several times. Values for link centrality are shown in Table 8. Table 9 lists links in each category, while Figure 9 shows the spatial distribution of groups throughout the state based on link centrality values.

Table 8: CALVIN links ranked by centrality. *Link centrality* sums the ratio of the number of shortest paths between two points in the network that pass through a link to the total number of paths between two points for all points in the network.

Link Name	Location	Un-weighted Link Centrality Value
San Joaquin River Reach 1	Delta	161,751
San Joaquin River Reach 2	Delta	148,907
CVPM 10 inflows and outflows	Central Valley	106,372
Sacramento River diversion	Northern	93,571
California Aqueduct Reach	Southern	85,675
California Aqueduct deliveries (Oak Flat, CVPM Region 10)	Northern	60,127
Friant-Kern Canal export from Millerton	Eastern Central	60,016
California Aqueduct Flow (Region 4 to Region 5)	Central	54,240
Friant-Kern Canal Reach 2	Central Valley South	49,138
Delta Exports to Central Valley and Southern California	Delta	48,828
California Aqueduct, diversion to Banks Pumping Plant	Delta West	48,744
Sacramento River outflow from Region 1 to Region 2.	Northern	45,998
San Joaquin outflow at Vernalis	Delta	45,355
Delta Exports from Tracy Pumping Plant	Delta	45,203

Figure 8: Grouping Links by Relative Ranking of *Link Centrality.* Values are not normalized

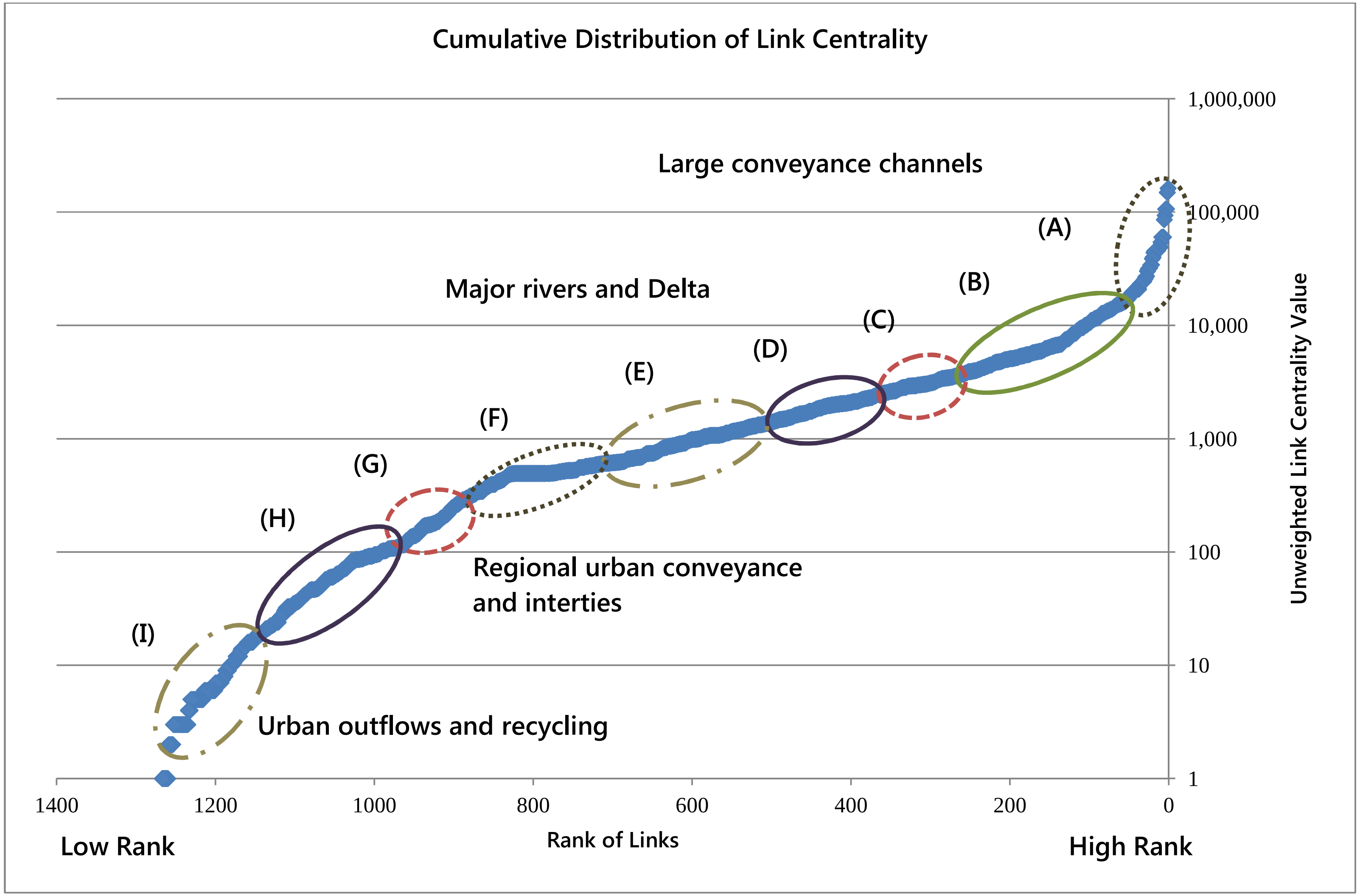
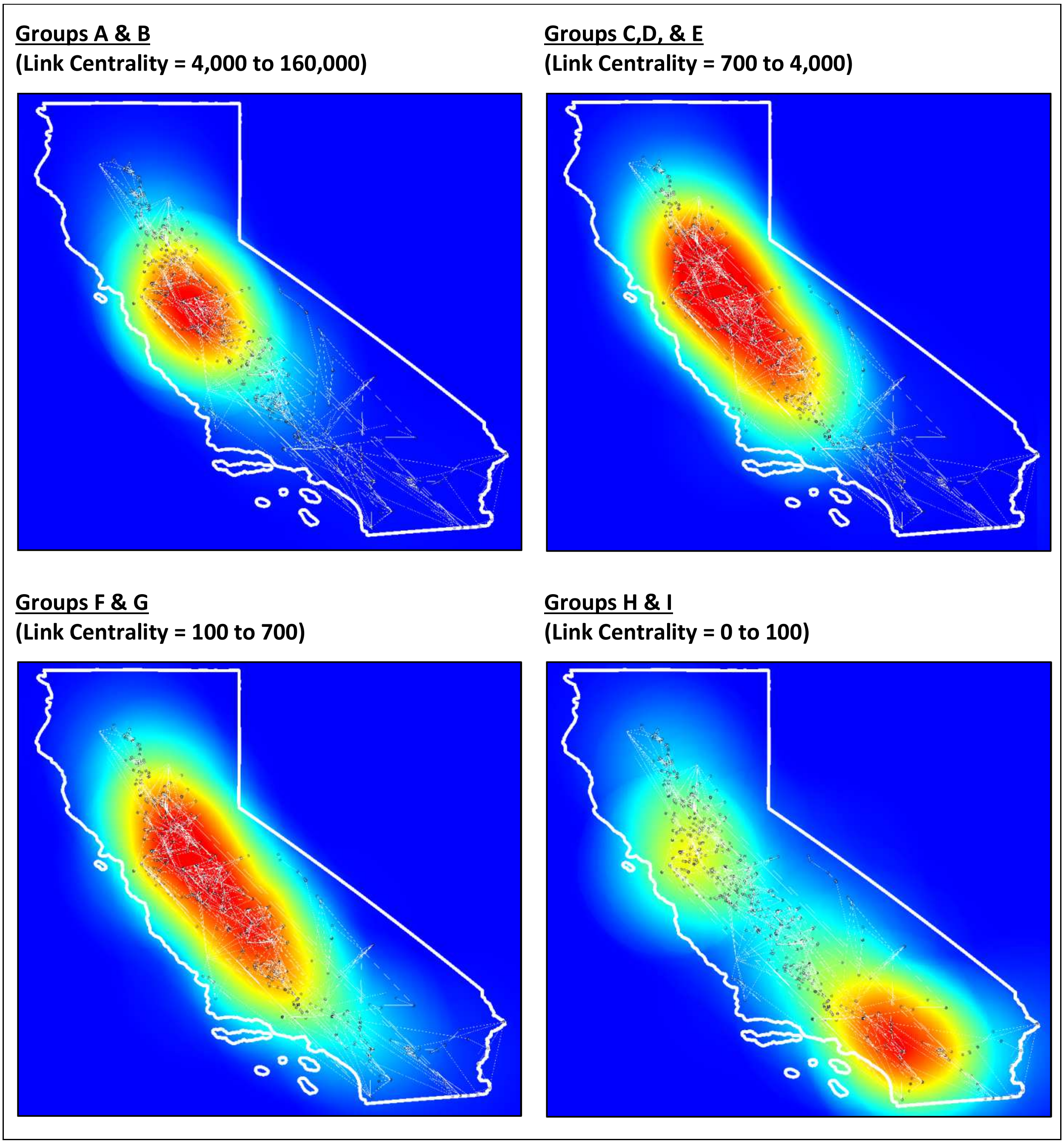


Table 9: Links associated with regions of the distribution of *link centrality* in Figure 9.

Label	Nodes	
(A)	California Aqueduct reaches (Oak Flat/San Jose, Dos Amigos Pumping, Banks Pumping); Delta Mendota Canal reaches (Tracy, CVPM 10) Friant-Kern Canal reaches	Sacramento River (Knight's Landing, Red Bluff) San Joaquin River reaches Tehama-Colusa Canal (CVPM 3 delivery)
(B)	California Aqueduct reaches (O'Neill Power Plant, Las Perillas and Wheeler Ridge Pumping Plant) Coastal Aqueduct Feather River reaches Friant-Kern Canal Englebright Dam releases Sacramento River (Freemont Weir, Cottonwood Creek)	San Joaquin River (Friant Dam, Gravelly Ford) South Bay Aqueduct Yolo bypass outflows to Delta Stormwater return flows to CVP Tuolumne River Yuba River
(C)	Agricultural groundwater pumping nodes (CVPM Regions 11,12,13) Friant-Kern Canal (Deliveries to CVPM 19,20) Kaweah River (Tulare Lake) Old River	Sacramento River (Clear Creek, Red Bluff reaches, Sacramento City) Stanislaus River Tuolumne River reach Yuba River
(D)	Agricultural groundwater pumping nodes (CVPM Regions 1-15 Demands) American River (Nimbus dam) Bear River Cache Creek California Aqueduct reaches (Buena Vista, Edmonston, Chrisman Pumping Plants) Cosumnes River reach Delta Nodes (CVPM Region 9, Mendota Canal) Feather River (CVPM 5,13, 16 diversions) Gianelli Pumping Plant	Los Banos Grandes Mallard Slough Putah Creek Sacramento River (Red Bluff to Ord Ferry, Sacramento City, Shashta Dam San Joaquin River reaches (riparian diversions, CVPM 11 & 12) San Luis Reservoir Wastewater Return Flows (Galt and Redding) Yolo Bypass (reach 1) Turlock Canal
(E)	Chowchilla Bypass EBMUD-CCWD Intertie Delta Cross Channel Folsom South Canal	Sacramento River to Delta Cross Channel Sacramento River to Freeport South Bay Aqueduct (Lake Del Valle) Trinity River
(F)	American River (Below Folsom Dam) Cross Valley Canal SFPUC-EBMUD Emergency Intertie	Fresno River Santa Ana Pipeline Santa Clara wastewater outflows
(G)	Castaic Lake (to MWD) Contra Costa Canal Colorado Aqueduct and Colorado River Feather River inflows to Lake Oroville Hetch Hetchy Aqueduct All-American Canal	Owens River New Don Pedro Reservoir San Diego Water Supplies SFPUC Sacramento River (Glenn Colusa Canal) Trinity River
(H)	Agricultural groundwater pumping nodes (CVPM Regions 18-20 Demands) Bakersfield municipal discharges Coachella Canal Crystal Springs Bypass Tunnel EBMUD-SFPUC exchanges Urban wastewater recycling Los Angeles Aqueduct	Los Vaqueros Reservoir New Don Pedro Dam New Melones Dam (Stanislaus River) Pardee Dam/Camanche Reservoir Santa Clara Valley groundwater recharge nodes Upper Owens River Central Valley wastewater return flows Whiskeytown Lake
(I)	Central Valley urban recycling nodes Los Vaqueros Pumping Plant diversions	Bay Area urban recycling nodes San Diego urban wastewater recycling

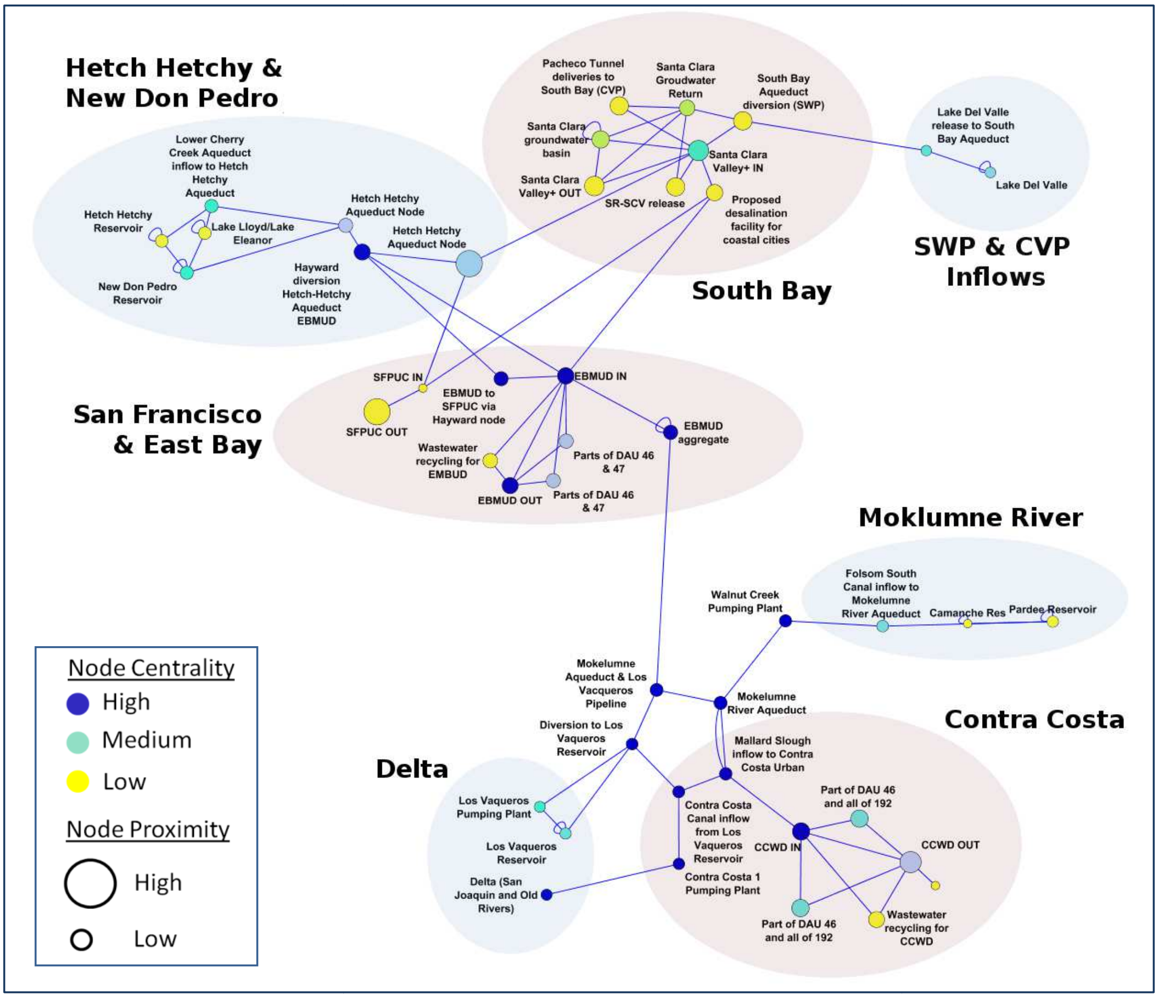
Figure 9: Spatial distribution of unweighted values of link centrality for all links in the state. The groupings (A, B, C, and D) correspond with Table 9. The raster colormap indicates the specified range of values of link centrality in each group, with links positioned based on their mid-points (difference between end-points). Links with high centrality values are clustered in the California Delta region, while links with medium and low centrality values are more dispersed throughout the state.



3.5 Visualization in smaller networks

While visualizing large networks can reveal broad trends in network structure, visualizing smaller networks can reveal more detail. Figure 10 shows the water distribution network for the San Francisco Bay Area, including upstream sources in the Sierra Nevada Mountains, aqueducts, and users throughout the Bay Area (not including Napa and Sonoma).

Figure 10: Bay Area water network through a cluster-based visualization. Node colors show node centrality, with higher scores denoting nodes that join communities (dark blue = high, yellow = low). Node size indicates closeness, which denotes how quickly water would flow from one node to surrounding nodes (larger node = high). Large, blue nodes are most important for connectivity.



Different aspects of operations can be emphasized and explored in the smaller network. Figure 10 uses color to show node centrality and size to show proximity of a node to its neighbors. Node centrality indicates the importance of a location within the network, while proximity indicates how quickly water would flow to neighbor nodes. Potentially important nodes are indicated by a larger size and dark blue color. Managers can use such exploratory tools to provide insights into network structure, validate operations, and communicate network characteristics to audiences.

3.6 Weighting network features to improve analysis: Capacity and Demand

The operation of water distribution systems is ultimately linked to water delivery. Two important characteristics for water delivery are capacity and demand. Both natural and constructed links have capacity limits. Integrating capacity with connectivity may provide a more practical view of overall connectivity for water distribution networks.

To test the value of weighting links by important parameters such as population and capacity, weights were applied to the San Francisco Bay Area water supply network, which includes upstream sources in the Eastern California Mountains, conveyance hubs in the Delta, and the major water users in communities near the San Francisco Bay.

As a simple measure to test the validity of weighting, the link centrality, B_{e_i}, was multiplied by the monthly capacity (C_i) of that connection in thousand acre feet (TAF), and the target demand (D_i) for that connection (in TAF), such that the weighted measure of centrality is equal to:

$$R_i = B_{e_i} * D_i * C_i \qquad (6)$$

Table 10 shows results with weighted and unweighted rankings for comparison. Similar to the whole network, many of the upstream and Delta connections ranked highly.

Table 10: Link Connectivity Rankings for San Francisco Bay Area Water Network

Description	Link Centrality	Rank	Annual Flow Target (TAF)	Monthly Capacity (TAF)	Rank: with FT and Cap	Composite Rank
San Joaquin River Reach (Upstream of CA Delta)	5,665	9	7,467	3,004	1	1
Mokelumne Aqueduct	40,868	1	271	30	10	2
Hetch Hetchy Release to New Don Pedro Reservoir	564	38	414	439	2	3
Mokelumne River Aqueduct Pumping Plant	6,771	7	271	30	12	4
Cherry Creek inflow to Tuolumne River	564	38	431	199	4	6
Pardee Dam Releases and Camanchee Reservoir Inflow	233	51	406	343	3	7
East Bay MUD: local storage release	4,129	11	271	27	14	8
Hetch-Hetchy Aqueduct	2,584	17	346	28	6	9
Crystal Springs Bypass Tunnel	2,600	16	219	20	18	11
East Bay MUD: Reservoir Urban Conservation	1,254	26	235	25	15	12
Napa-Solano Urban Conservation	1,953	22	158	18	19	13
Diversion from Pardee Res. to Mokelumne R. Aqueduct	344	47	271	30	13	14
Diversion from Hetch Hetchy Reservoir to Canyon Tunnel	257	49	336	28	7	15

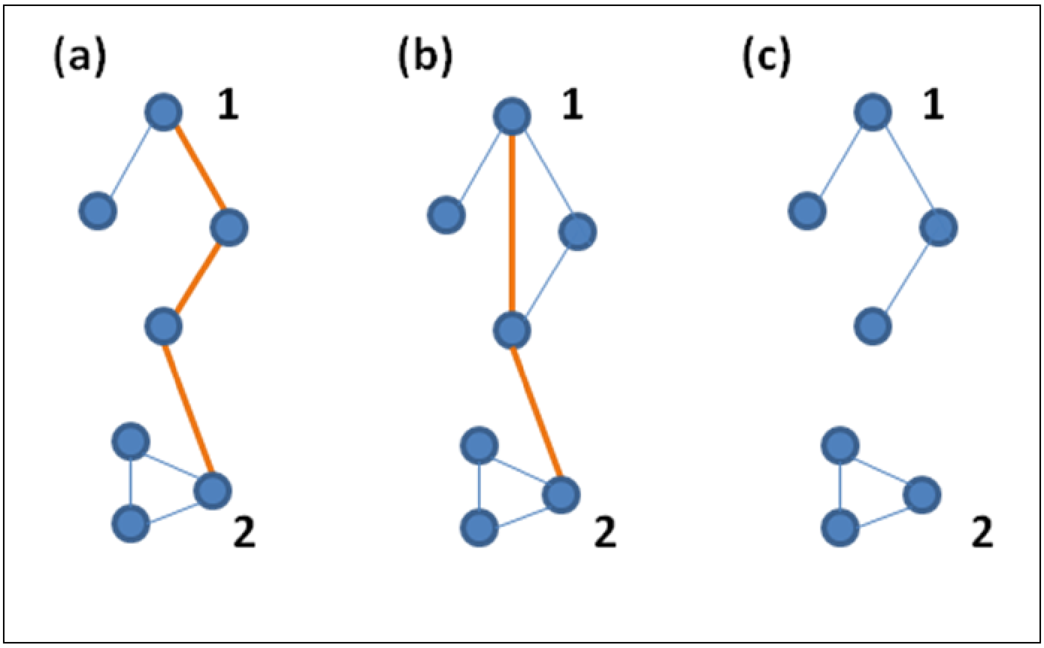
In the unweighted measure of link centrality, the Mokelumne Aqueduct and ranked highly. After weighting by capacity and target flow, several reaches of the Mokelumne Aqueduct still ranked high, but other links, especially rivers and reservoirs with a large capacity, increased in relative rank. The San Joaquin River ranked highly in both the weighted and unweighted cases. Weighting using values for capacity and flow can help to integrate the physical and hydrologic parameters with measures of network structure to improve the applicability of network analysis approaches.

4 Breaking the Network

Piecewise and cumulative removal of nodes can test the effects of network degradation on metrics such as connectivity, clustering, average path length and central dominance, which characterize network structure and performance. For example, Figure 11 illustrates how removing nodes affects path length calculations.

I analyzed network degradation and resilience in CALVIN to assess how network theory metrics characterize CALVIN performance after losing important links. The analysis removed key links identified in Section 4 using a both a piecewise and cumulative procedures. Broken links included: 1) the California Aqueduct, 2) the Sacramento River, 3) the San Joaquin River, 4) the Feather River, 5) the Friant-Kern Canal; 6) the Delta-Mendota Canal, 7) Delta conveyance, 8) the Hetch Hetchy Aqueduct, 9) the Mokelumne Aqueduct, 10) the Los Angeles Aqueduct, and 11) the Colorado River Aqueduct. Numbers 1-7 are system-wide features, while numbers 8-11 are regionally focused features.

Figure 11: Changes in average path length by adding and subtracting links. The shortest path between nodes 1 and 2 in (a) is three steps. Adding a link in (b) decreases the distance between nodes 1 and 2 to two steps and reduces the overall average path length in the network. Yet, removing a link as shown in (c) can also decrease path length if it fragments the network and average path length is still calculated for all nodes but only using the connected nodes. For water resources, (c) would represent a supply network based on more regional sources, while (a) and (b) represent different versions of more centralized schemes.



The piecewise removal procedure (Table 11- top) analyzed the importance of individual nodes. Removing California Aqueduct nodes had the greatest effect in decreasing central point dominance (0.024 to 0.022), meshedness (0.248 to 0.266), average path length (22.47 to 18.8), and clustering (0.066 to 0.069). These changes indicate a decrease in system wide connectivity, which is related to both the centrality of the aqueduct as well as the number of nodes (25) CALVIN uses to model it.

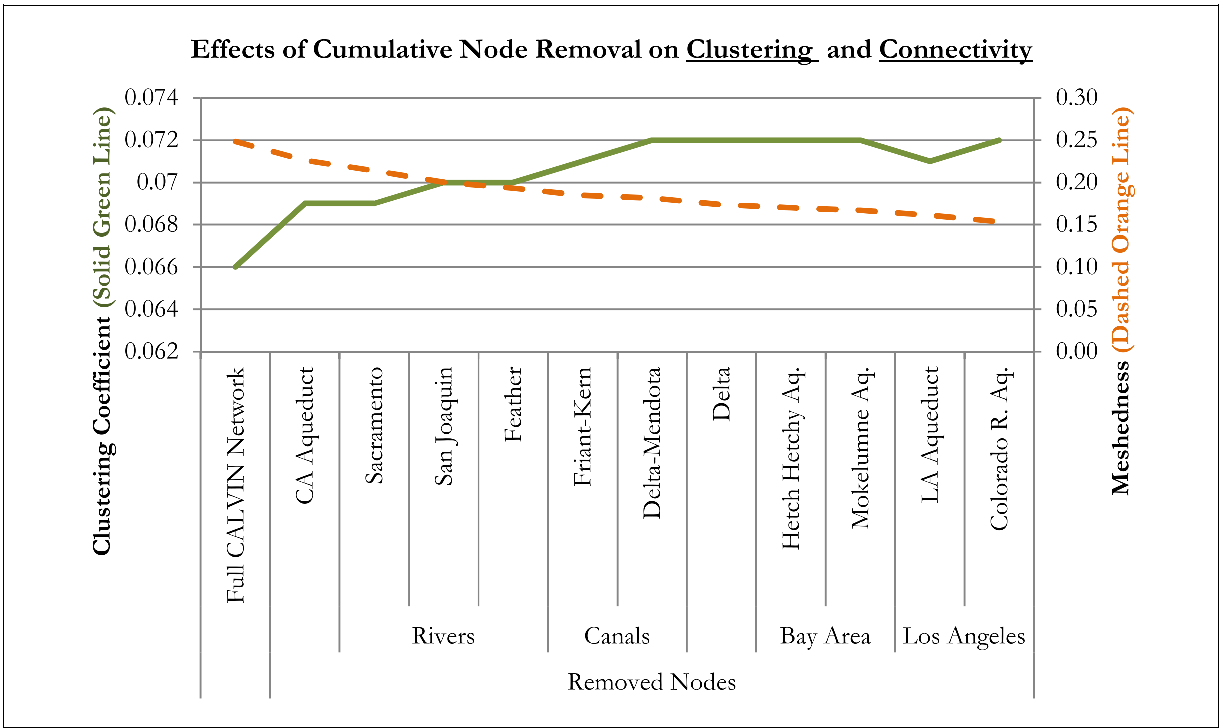
The cumulative removal procedure (Table 11- bottom) analyzed the effects of cascading network degradation. Nodes and links were successively removed (from top to bottom in Table 11). Central point dominance, which assesses the importance of a few central nodes across the network, changed depending on which nodes were removed. Removing the California Aqueduct made the network less dominated by central nodes, represented by the decrease in central point dominance. Removing regionally-important nodes such as the LA Aqueduct, however, did not affect overall network structure.

Table 11: Effects of piecewise (top) and cumulative (bottom) removal of important nodes and links throughout the statewide system on measures of connectivity, dominance, and clustering.

		Piecewise Removal					
Network		**Central Point Dominance**	**Meshedness**	**Path Length**	**Clustering Coefficient**	**Nodes**	**Links**
Entire CALVIN		0.024	0.248	22.47	0.066	858	1283
Randomized CALVIN		-	-	10.601	0.0002	858	-
Broken Links: System wide							
CA Aqueduct		0.022	0.226	18.8	0.069	833	1208
Rivers	Sacramento	0.024	0.237	23.66	0.067	846	1246
	San Joaquin	0.02	0.235	24.341	0.067	844	1240
	Feather	0.024	0.242	23.52	0.066	853	1264
Canals	Friant-Kern	0.024	0.241	23.63	0.067	852	1261
	Delta-Mendota	0.024	0.245	22.727	0.066	857	1275
Delta		0.024	0.241	22.683	0.067	849	1257
Broken Links: Regional							
Bay Area	Hetch Hetchy Aq.	0.022	0.245	22.59	0.066	855	1273
	Mokelumne Aq.	0.024	0.246	21.965	0.066	856	1276
Los Angeles	LA Aqueduct	0.024	0.243	22.201	0.066	853	1267
	Colorado R. Aq.	0.024	0.242	22.412	0.067	850	1261
		Cumulative Removal					
Broken Links: System-wide							
CA Aqueduct		0.022	0.226	18.8	0.069	833	1208
Rivers	Sacramento	0.022	0.214	20.04	0.069	821	1171
	San Joaquin	0.019	0.200	12.39	0.070	807	1129
	Feather	0.019	0.193	13.70	0.070	802	1111
Canals	Friant-Kern	0.019	0.185	13.86	0.071	796	1089
	Delta-Mendota	0.020	0.181	11.58	0.072	788	1073
Delta		0.020	0.174	11.43	0.072	779	1049
Broken Links: Regional							
Bay Area	Hetch Hetchy Aq.	0.019	0.170	10.64	0.072	776	1039
	Mokelumne Aq.	0.019	0.167	9.88	0.072	774	1032
Los Angeles	LA Aqueduct	0.019	0.161	9.93	0.071	769	1016
	Colorado R. Aq.	0.019	0.154	10.02	0.072	761	994

While meshedness (indicating connectivity) decreased with piecewise removal, the clustering coefficient increased, indicating stronger local groupings. Figure 12 shows the change in clustering (clustering coefficient) and connectivity (meshedness) after cumulative removal of important links.

Figure 12: Effects of cumulatively removing key system nodes on (a) *Clustering Coefficient* and *Meshedness*. Nodes are removed cumulatively from left to right. The graph shows the growth of clusters (higher clustering coefficient) and reduced connectivity (lower meshedness).



Average path length is a divergent metric. As important links are removed, average path length typically increases, since the remaining paths between any two nodes are less direct. However, when removing an important link divides (fragments) the network into two or more sub-networks with disconnected nodes, path length will decrease. To compensate, research developed an index of efficiency, E, which is defined as the sum of all the reciprocals of path lengths between two nodes (Smith 1988; Latora & Marchiori 2001):

$$E = \frac{1}{v(v-1)} \sum_{i \neq j} \frac{1}{d_{ij}} \qquad (7)$$

Efficiency addresses the issue of disconnected nodes, as the reciprocal of an infinite distance between the disconnected nodes *i* and *j* is equal to zero. Thus, efficiency is larger in a more connected network. Figure 13 and Table 12 below compare values of these two metrics for the CALVIN analysis.

Figure 13: Effects of network degradation from cumulative removal of nodes on two potential measures of network efficiency defined in literature: *Average Path Length* and *Efficiency*. While average path length declines due to fragmentation and is "ill-defined" for fragmented networks, efficiency declines indicating reduced performance in the network with removed nodes.

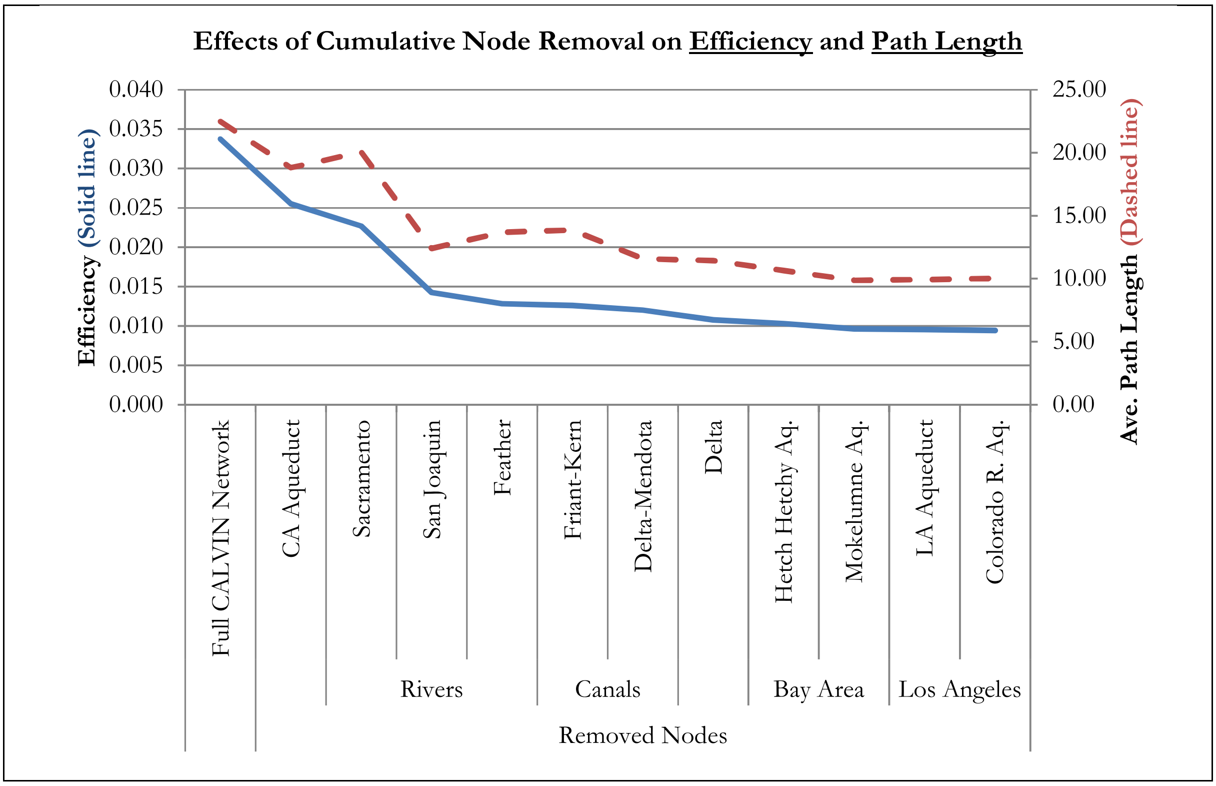


Table 12: Comparing effects of network fragmentation on metrics of efficiency in CALVIN.

		Cumulative Removal			
Network		**Path Length**	**Efficiency**	**Nodes**	**Links**
Broken Links: System-wide					
CA Aqueduct		18.8	0.026	833	1208
Rivers	Sacramento	20.04	0.023	821	1171
	San Joaquin	12.39	0.014	807	1129
	Feather	13.70	0.013	802	1111
Canals	Friant-Kern	13.86	0.013	796	1089
	Delta-Mendota	11.58	0.012	788	1073
Delta		11.43	0.011	779	1049
Broken Links: Regional					
Bay Area	Hetch Hetchy Aq.	10.64	0.010	776	1039
	Mokelumne Aq.	9.88	0.010	774	1032
Los Angeles	LA Aqueduct	9.93	0.010	769	1016
	Colorado R. Aq.	10.02	0.009	761	994

The relationships between all of the metrics can reveal tradeoffs in structure and performance of water resource systems. A more highly-clustered system with shorter distances between sources and users would be more efficient, which could indicate lower transportation costs. The locally-reliant network could also be easier to administer if local decision-making allows users, managers, and suppliers to interact more freely. Yet, these systems would also be subject to local environmental variability. If a regional drought or equipment failure occurs, backup options are likely fewer. In contrast, a system dominated by central nodes can ease the problems of environmental variability if it pulls water from a wider region. It can also assist in developing economies of scale for construction and operation. Central systems, though, would have higher costs for conveyance and could be subject to issues of reliability and attack. A mix of centrally-dominated and local supplies can help mitigate variability of rainfall while maintaining local control, but redundant functions require more resources. Thus, the balance between centralized and dispersed sources is dependent on local conditions. In California, large differences in climate throughout the state mean that connectivity helps to mitigate environmental variability by allowing water to flow from areas of higher to lower availability. The network analysis measures for central dominance, efficiency, and clustering provide potential tools for analyzing such trends.

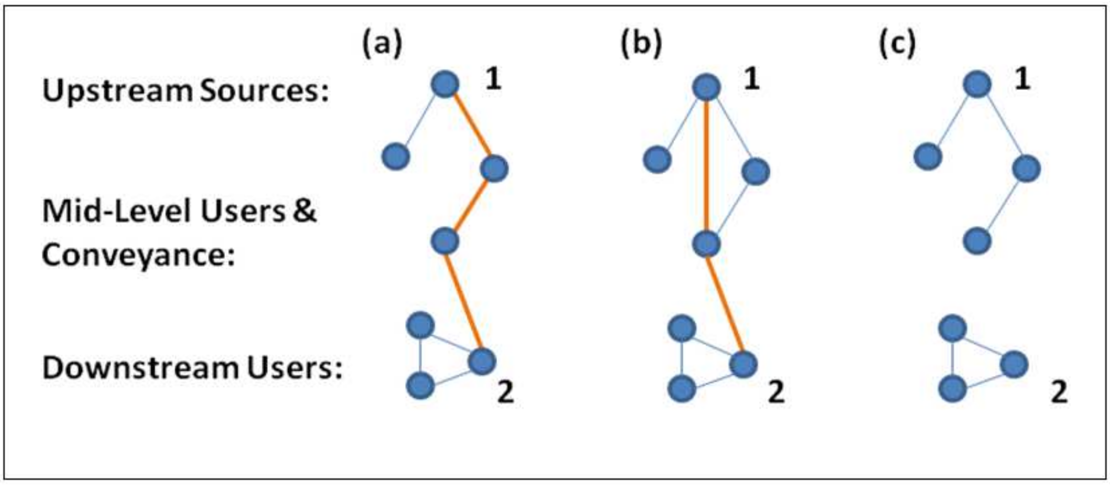
5 Discussion

In theory, resilience and connectivity are related. How does this insight relate to the function of an integrated infrastructure network with environmental and technological components? Further, are there implications specific to water infrastructure networks? Network theory metrics of CALVIN showed high potential for assessing system connectivity. Building on this, the network analysis of CALVIN provides insights for resilience related to: 1) limited and unlimited connectivity, 2) tradeoffs in efficiency and performance, 3) the importance of local conditions, and 4) the purpose of resilience planning.

Limited or unlimited connectivity: Many types of networks exist with different properties. For instance, the published analysis of the Southern California power grid showed it to be small-world but scale-limited, since nodes were constrained in the number of connections they could take on. The CALVIN network, however, may be scale-free, meaning that there are some nodes that have a large number of connections and, at the network level, the number of connections for nodes is not constrained. California water infrastructure was developed during a time of relative (or perceived) abundance of water and capital. Connections between users and major features, such as the California Aqueduct and canals, were not in principle constrained. Central supplies increased connectivity and central dominance, which hedged against variability of more local sources. Users throughout the state signed on to large-scale construction. In time, however, users and managers realized that major components such as the State Water Project were over allocated (Reisner 1993). Thus, the physical structure of the network was built to increase centralization with underlying assumptions of readily available and transferable water. Nationwide, during this era of water resources management, many planners of regional or large-scale distribution systems tended to assume “unlimited economies of scale for water treatment and delivery systems,” which often led water utilities to expand service areas beyond efficient regions (Clark & Stevie 1981). Yet, though the physical capacity of water infrastructure networks may not be constrained, actually supply is increasingly limited.

In many networks, adding more components (nodes or links) increases connectivity and flexibility, but this assumes a technological solution. More routers can provide additional hubs. More power lines provide greater transmission capacity. For water infrastructure, however, adding another canal means little if there is no additional water. Moreover, while water resource networks are subject to environmental and physical constraints, different types of water infrastructure networks have different constraints. Water distribution systems within cities are more analogous to networks that use “technological” solutions of installing additional components to address connectivity and reliability issues. An additional pipe connection in the city could increase meshedness, flexibility, and resilience. Yet, urban water infrastructure networks should not be assumed to follow scale-free properties (Venkatesh et al. 2011). For the regional system, connections are only useful when they provide additional supplies. The resilience of a purely technological system of pipes differs from resilience in an integrated social-technological-environmental system. In California, urban water managers have had to change from a scale-free to a scale-limited perspective, seeking additional local connectivity through reuse, groundwater banking, and water transfers. At both the local and regional level, the solutions for connectivity are not simply technological, but instead span the "portfolio" of water supply options. Figure 14 illustrates these concepts further.

Figure 14: Considering connectivity for local reliance and system-wide conveyance in nested networks. The (a) and (b) networks are more centrally-dominated, with upstream sources flowing throughout the network. Adding the additional link in (b) to increase efficiency only makes sense if there is enough water to convey. The (c) network is more dominated by local and regional reliance. Efficiency may be higher, but it can also be subject to local environmental variability. Each dot may represent a sub-network, such as a metropolitan distribution system. Connectivity in these sub-systems may be managed with more technology, while at the level of the wider network, contracts, transfers, and non-technological factors may have more influence on connectivity.



Scale-free networks show the peculiar property of being resilient to random failures but susceptible to targeted failures of major nodes (Albert et al. 2000). To increase resilience in a scale-free network for both random and targeted failures, decentralization seems appropriate. Yet, in California, the earlier, more decentralized era of local reliance would doubtless seem less reliant. Decentralization within a city can help to protect against targeted attacks or failures of large nodes, both of which are relatively unlikely, but water use in major cities almost always exceeds local supplies. Regional networks are commonly needed. For these networks, economies of scale dictate planning. Thus, considered at multiple scales, hybridization of both centralized and distributed designs may offer more resilience for a resource system of environmental and technological components.

Tradeoffs in efficiency and performance: The network metrics show several tradeoffs. As central dominance decreases, efficiency increases as characterized by shorter average distances between nodes in the network. Engineering systems were designed to maximize efficiency through economies of scale, but alternate designs could capitalize on the inverse relationship between centralization and efficiency. Locally-available water has lower transit costs. New technologies for water treatment and more integrated analysis of benefits across sectors (energy, water, food) can change the economics by making local supplies more available and cost-effective. This could increase efficiency and resilience, but only if local supplies have centralized backup sources. Similarly, as connectivity (meshedness) decreases, clustering increases. In the era of resource constraints, "clustering" of resources will likely grow as cities seek more local reliance. It seems unlikely, however, that they will be able to muster purely technological solutions to such problems without increasing efficiency and decreasing use.

The importance of local conditions: Designing resilient water supply systems must account for local conditions. In rainy cities, for instance, distributed sources can provide a greater percentage of supply. If arid cities sought to increase resilience by moving entirely from distant central supplies to distributed local sources, though, system performance would likely plummet. Cities and the engineering feats that fuel them are inherently subject to environmental constraints. Arid cities and growing cities in general can seek technological solutions to increase local reliance, but the realities of environmental limits caution against singular approaches. In addition, the nature of threats differs with location. Planning for resilient systems is inherently local and related to the complex collection of factors that influence development, resource use, and growth.

The purpose of resilience planning: Distributed sources in scale-free networks reduce susceptibility to targeted attacks. This is relevant for critical infrastructure and national security concerns, where an attack would target important system components. It is hard to attack all sources at once. The alternative likelihood of a simultaneous random failure of these sources is small with proper maintenance, but grows if infrastructure is not maintained. Rather than basing reliability analysis on the relatively unlikely event of joint technological failures, mangers should focus on more variable environmental conditions. While catastrophic events such as terrorist attacks capture public discussions, motivate public planning, and speed new funding, the more chronic sources of failure such as maintenance and long-term climate variability likely pose greater threats. Planning a more reliable system does not necessarily call for decentralization to protect against targeted attacks, but instead calls for a more hybridized system that integrates the efficiency and resilience benefits of distributed supplies with the reliability of central sources to manage the collection of water supply reliability factors. The major challenge is to balance redundancy and streamlining across multiple sources of failure. While past planning processes optimized for streamlined efficiency, future procedures can optimize for hybridized efficiency.

Order and scales: In a system, order is represented as noticeable traits or patterns. Structural order such as a grid layout, or mathematical order such as scaling properties, can reveal recognizable patterns. Order may be systematic or characteristic (Marshall 2009). *Systematic order* applies consistently to all members or components of the network. Systematic order in systems such as infrastructure networks or cities likely arises from hard planning rules and conscious decisions. *Characteristic order* refers to order that arises from underlying properties affecting the network components, but not through central planning. A local water pipe network is likely highly systematic in its order, since clear construction and management rules went into its planning. At a statewide level, however, decisions on system construction, management, and function are made by managers at many levels, which may or may not coordinate. Some properties, such as the apparent power law in node degree distributions, may be characteristic in that they arose not out of specific planning rules, but instead as a function of underlying system properties that governed how actors at many levels made decisions. Thus, when analyzing water infrastructure networks at different levels, recognizable order may originate from different sources.

Limitations: These analysis results are subject to several limitations. First, as a simple model, CALVIN may not fully represent the California water infrastructure network. The scale-free characteristic may be related to the modeling approach and network design rather than the actual characteristics of the system. Second, while network theory metrics present new opportunities for analysis, more indicators are not necessarily better. The network theory metrics presented and give insights, but the expanding frontier of research in unified theories of complex networks means that interpretations of network science metrics could change. Third, the analysis of the whole CALVIN network did not weight a particular node or link using capacity or scarcity costs. Integrating such weights into the analysis would probably alter results. Fourth, the treatment of the topographic network as a set of points, spaced equidistant from neighbors, simplifies the geographic reality of the actual network. Fifth, the analysis did not incorporate any stochastic elements, which are important considerations for resilience and reliability. Sixth, the analysis did not address connectivity between scales and functions in the water infrastructure network. This is an important component of the theory linking resilience and networks in ecology. Finally, since network theory applications are relatively new for infrastructure generally and water in particular, their interpretation is most relevant to compare different configurations of the same network.

6 Conclusions

In ecological theory, connectivity and resilience are related. Network theory metrics provide tools to analyze connectivity and empirical analysis approaches for resilience. A large-scale water infrastructure network model, CALVIN, was used to analyze common network theory metrics and implications for resilience in planning and management. Key network analysis metrics, including node and link centrality, meshedness, central dominance, clustering coefficient, and path length identified important nodes and links in the entire CALVIN network and the Bay Area sub-network. Network analysis provides tools to assess system wide performance and function rather than singular or small collections of facilities. Exploring properties of water infrastructure networks can contribute to the growing body of literature in unifying theories of networks and complex systems, while also yielding insights specific to improving water resources management. For water resources, network analysis metrics approaches are in their infancy. Analysis metrics are most useful to compare scenarios within a network or help knowledgeable managers test and confirm insights regarding important links and nodes in large networks.

Network visualization algorithms were used to illustrate and explore network structure for the CALVIN network. Such visualizations can complement existing geospatial analysis tools and network schematics, which are likely to grow. Web-based platforms can provide tools for dynamic visualizations. Visualization algorithms using network theory provide flexible platforms with customizable colors, sizes and shapes, which can help to display multi-dimensional data and identify trends. Network visualization algorithms can be readily applied to many common water resource network models and may offer the most useful aspect of network theory for water resources engineering, given the aforementioned difficulties in normalizing numerical metrics and indices.

The research can be extended in several ways. As a cross-disciplinary tool, network analysis could also overlay multiple networks of environmental, technological (infrastructure), and social nodes. In addition, the analysis can incorporate weightings and groupings to integrate capacity and scale. This would help the analysis address reliability along with testing the theoretical foundations of ecological resilience and connectivity. Finally, while network theory focuses on nodes and links, new connections can also address reliability and resilience. Incentive programs to increase conservation, progressive rate structures that charge higher rates for more water use, water markets, organizational agreements, and the entire "portfolio" of water management options are all important contributors to meeting water demands. Integrating these factors into the analysis could improve insights.

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Appendix

Table 13 below details a full-listing of analysis metrics and indices for use in analyzing network structure and connectivity.

Table 13: Complete Listing of Network Analysis Measures and Indices

Indicator	Description	Symbol	Formula
Network-Level Measures			
Diameter	Length of the shortest path between the most distant nodes in a graph	d	n/a
Number of cycles	Number of closed paths in a graph	u	$u = e - v + p$
Network-Level Indices			
Alpha Index (Meshedness coefficient)	Ratio of the actual number of cycles in a network to the maximum possible number of cycles	α (r_m)	$\frac{u}{2v-5}$
Beta Index	Relates the number of edges (links) to the number of nodes (vertices)	β	$\frac{e}{v}$
Gamma Index (Link Density)	Measures connectivity by relating the number of observed links and the number of possible links	γ	$\frac{e}{3(v-2)}$
Eta Index	Average length per link	η	$\frac{L(G)}{e}$
Characteristic Path Length	Average of the shortest path-lengths in a graph, where i and j are two nodes	l	$\frac{1}{v(v-1)}\sum_{i \neq j} d_{ij}$
Local Clustering Coefficient	Average of the clustering coefficients of all nodes with more than 2 connections. The clustering coefficient calculates a ratio of: the number of edges between node *i* and its neighbors; and the maximum number of edges between node *i* and its neighbors. Higher average clustering coefficients indicate more clustered networks.	C_i	$\frac{1}{n}\sum_{i \neq j} \frac{v_i}{k_n(k_n - 1)}$
Central Point Dominance (Centrality of Graph)	Measures dominance of a single point in controlling the linkages within the network. It is the average difference between the most central point and all others. A higher value indicates network centrality. Traditionally used for undirected networks.	c_b	$C_b(k) = \frac{\sum_{i=1}^{n}[c_b(n_k) - c_b(n_i)]}{n-1}$ *Where c_b (n_k) is the max node centrality value, c_b (n_i) is relative betweenness centrality value for any node i, and n is # of nodes.*
Node-Level Measures			
Node Centrality (Betweenness Centrality)	Number of shortest paths between two points divided by the number of shortest paths between two points that pass through a node. Measures node importance.	C_b	$C_b(k) = \sum_{i \neq j \neq k} \frac{g_{ij}(k)}{g_{ij}}$ *Where g is the number of shortest paths and g(k) are shortest paths passing through k.*
Degree	The number of links attached to a node. In directed networks, differences between in-degree and out-degree may reveal characteristics.	o	*n/a*

Indicator	Description	Symbol	Formula
Closeness (centrality)	The reciprocal of the average shortest path length	C_c	$C_c(k) = \frac{1}{L}$ *Where L is the average length of a shortest path between k and any node*
Radiality	Degree to which a node's connections reach out into the network (Valente & Foreman 1998)		$C_R(k) = \frac{\sum_t (D(G) + 1 - d_g(v,t))}{(n-1) * D(G)}$ *Where d_g is the average shortest path length of a node, n, and D(G) is the diameter of the connected component. Ranges from 0 to 1.*
Link Measures			
Link Centrality (Link/Edge Betweenness)	The number of shortest paths between two nodes *s* and *t* that go through an edge, divided by the total number of shortest paths that go from *s* to *t* (Newman & Girvan 2004; Assenov et al. 2007).	B_e	$B_e(k) = \sum_{i \neq j \neq k} \frac{h_{ij}(k)}{h_{ij}}$ *Where h_{ij} is the number of shortest paths between two nodes (i and j) and h(k) are shortest paths passing through link k*

Table 14: Top Ranked Nodes by Measures of Centrality

Node Name	Type	Measures of Node Centrality: Avg. Shortest Path Length	Node Centrality	Closeness Centrality	Clustering Coefficient	Degree	Neighborhood Connectivity	No. of Directed Edges	Connected to Nodes with Multiple Links	Radiality	Topological Coefficient	Number of Top Rankings
California Aqueduct Deliveries: Friant-Kern & Fresno	Connection Node		x	x		x		x		x		5
Mendota Pool	Reservoir		x	x		x		x		x		5
New Don Pedro Reservoir	Reservoir			x		x		x	x	x		5
San Joaquin River diversion to CVPM 10	Connection Node		x	x					x	x		4
Feather River inflow to Sacramento River	Natural Supply		x		x			x	x			4
La Grange Dam	Reservoir			x		x		x		x		4
California Aqueduct diversion to CVPM 10	Connection Node			x					x	x		3
Millerton Lake	Reservoir		x	x				x		x		3
Stanislaus River diversion	Connection Node		x	x						x		3
New Melones Reservoir	Reservoir			x	x					x		3
Lake McClure	Reservoir			x	x					x		3

Chapter 7

Conclusions

> *A mind which had the powers requisite to deal with such a problem in a proper manner and was brilliant enough to perceive the solutions of it… such a mind, I say, could from a continuous arc described in an interval of time, no matter how small, by all points of matter, derive the law of forces itself… Now if the law of forces were known, and the position, velocity, and direction of all the points at any given instant, it would be possible for a mind of this type to foresee all the necessary subsequent motions and states, and to predict all the phenomena that necessarily followed from them.*
>
> - Robert Joseph Boscovich, Theoria philosophiae naturalis (1763)

> *Theories are cheap; they cost only the time and effort of the theorists and these can be had quite inexpensively.*
>
> - David Easton, A Systems Analysis of Political Life (1965)

1 Question and Approach

This dissertation primarily sought to understand and explain evolution in urban water infrastructure through descriptive and quantitative methods. Today's urban water systems are transitioning to new designs that seek to reduce resource use, improve public understanding, deal with capital shortages, integrate new technologies, and manage increasing complexity across sub-systems. Innovation in infrastructure systems, though, is hampered by past capital investments and organizational inertia. Changes in complex infrastructure systems, which are influenced by many technological, socio-economic, and environmental factors, highly influence design and management approaches. No one analysis technique or model can adequately describe emerging trends in urban water. The methods in this dissertation present a collection of approaches from various disciplines needed to understand past and future trends. This collection, nevertheless, is not comprehensive.

In particular, the chapters highlighted several important themes and analysis approaches relevant to studying urban water and environmental systems. Urban environmental history analysis provides a foundation to understand why our current systems exist and what trends are emerging. Policy analysis uses a flexible collection of techniques that combine economic, political and technical analysis to inform cost-effective and equitable strategies for public infrastructure management. Optimization is a useful tool to sort through many potential solutions, identify promising solutions, and understand decision tradeoffs between multiple objectives. In particular, the chapters using optimization presented models for stormwater and water resource systems that inform our understanding of the development of systems rather than present absolute policy judgments. Finally, network analysis offers a set of analytics that combine metrics and visualizations to support empirical analysis of increasingly relevant topics for infrastructure and cities, including networks, complexity, and emergence. Taken together, the techniques, models, and visualizations enlighten our understanding of evolution in urban water infrastructure designs and better connect management of this infrastructure to the environmental and economic processes in and around cities.

2 Summary of Conclusions

The research identifies several important conclusions related to the evolution of and emerging trends in urban water and environmental management. The interdisciplinary approach provided both broad insights as well as specific theoretical and applied contributions.

2.1 Thematic Contributions

Several broad thematic conclusions follow from the research.

1) ***Urban water innovations are likely driven more by economics and emerging threats, not environmental quality.*** Similar to the early twentieth century, cities will likely lead as innovators for implementing and funding new technologies for a variety of reasons. Chapter 2 described the progression of urban water infrastructure innovations through the twentieth century. Moving forward, new technologies offer opportunities to improve resource use or environmental quality without sweeping new regulations or broad social changes. Many cities of the twenty-first century, both industrialized and industrializing, will face significant, perhaps existential, threats from rising sea levels, more frequent storms, and reduced resources. Such threats will motivate cities to changes policies and invest in infrastructure. Also, as shown in the Metropolitan Area Stormwater Model presented in Chapters 3 and 4, low-cost designs explain much of the evolution of urban stormwater systems. Yet, at the same time, the highly-regionalized approach to innovation can also exacerbate environmental externalities. Up to the mid-twentieth century, regionalized approaches to urban water management practices created significant environmental quality issues, as cities dumped effluent into environmental sinks with downstream repercussions. To prevent a reoccurrence of these trends in a twenty-first century fashion, national and state/provincial roles for government remain necessary.

2) ***Flexibility in water infrastructure systems, which improve cities' ability to respond to risks, consists of innovations in both technology and management.*** Cities secure access to water resources to drive growth. With increasing variability from climate change and resource scarcity, urban water managers need flexible systems to moderate uncertain supplies. Many cities will continue to develop more flexible infrastructure designs that increase a system's capacity to respond to chronic (long-term drought) or acute (hurricanes, floods) events. For instance, in Southern California, water utilities inject groundwater during wet years for storage and later extraction during droughts. At the urban scale, hybridized systems include both hybrid designs (distributed and centralized approaches) and hybrid management (community and expert involvement). These will likely grow. Traditional water management approaches emphasized technological solutions and increasingly affordable innovations such as water reuse and desalination provide high-tech capabilities. Yet, perhaps more important, management innovations such as water transfer agreements and citizen engagement, can go far to mitigate uncertain resource demands.

3) ***Water infrastructure systems are complex with planned and unplanned aspects.*** Traditional engineering design emphasizes the role of central planning and management. As described in Chapter 2, water infrastructure systems have been highly planned for centuries. In an urban water pipe network, managers typically know network structure, operations, and the planning rules that led to its creation. Yet, researchers increasingly recognize complexity in urban systems, which may breed properties of scaling, emergence, and non-linearity (Bettencourt et al. 2007). Evolutionary systems theory draws from physics, statistics, urban planning, economics, and sociology to describe how system properties can emerge from the collective decisions of many actors without top-level planning. Chapter 6 showed how the California state-wide water distribution system has unplanned aspects embedded in its design and connectivity. Many aspects of the system were centrally planned, such as the specific layout of major conveyance links. Yet, the interconnectivity of these links follows a scaling law that was not implemented by a single central planner, but was instead a product of collective economic and resource decisions from planners over decades. Chapter 6 revealed emergent properties for a large-scale network, but such unplanned aspects may influence operations at multiple scales of water infrastructure, including neighborhoods, metropolitan areas, and regional networks.

Cities can recognize this role of "un-planning" to improve operations. Today, cities are considering how to disperse some decisions for water management. Low-impact development and green infrastructure transfer some management responsibilities from central planners to private landowners. The potential for rainwater capture and harvesting, as well as direct potable reuse, may make homeowners responsible for design, similar to home heating and cooling. Dispersing such responsibilities creates a distributed decision-making model with increased failure risks as well as the potential for complexity and emergence. If managers can understand how to influence these "unplanned" system properties, rather than seek specific targets, they could improve system-wide outcomes. For instance, in a water distribution network, water managers could facilitate water transfers but shape how such transfers occur, with the goal of promoting more regionalized water management, improved groundwater quality, or other goals. Water managers will grapple with such questions in the future as complexity and uncertainty are recognized in infrastructure operations.

4) ***Green infrastructure uses technology to enhance landscapes and environmental processes.*** Urban water planning traditionally recognized local environmental constraints of water availability and runoff removal, but sought to transcend them using infrastructure and technology. Once cities altered the permeability of soils and created flood issues, cities built storm sewer conveyance to remove water. Today, interest in human alterations of urban ecological processes is fueling an improved understanding of how cities interact with local environments. Urban managers seek more livable cities that promote economic development and reduce expected costs of infrastructure development and environmental hazards. Infrastructure development in future cities will combine new technologies with design and planning to: 1) create cities that seek to function more like undisturbed environments when "natural" elements provide adequate service provisions (i.e. runoff), and 2) augment the ability of natural environments when inadequate to meet a desired level of service to urban residents. For instance, Chapter 3 showed how *green infrastructure* approaches to managing stormwater become more cost-effective with changing economics and regulatory policies. Cities will use hybrid designs to develop the next era of urban landscapes. These approaches mimic and enhance natural processes using technology and design to augment the ability of natural environments to remove pollutants and retain runoff. Across many urban systems, technological enhancement of environmental processes will try to simultaneously improve urban life (reduce pollution) and promote economic development (revitalization and higher real estate values).

5) ***Resilience has many conceptions across fields, but is relevant to the collective risks cities face today.*** Risk in networked systems is difficult to assess. Traditional risk assessment processes, which estimate event probabilities and the associated consequences, may fail to recognize the compound effects of several events on a system. "Globally-networked" risks present large planning challenges to mitigate uncertainties in highly interdependent systems that combine both natural and human sub-systems (Helbing 2013).

Resilience is an increasingly popular term for planning in natural resources, cities, and many other types of systems. The term is broadly flexible and addresses uncertainty in planning and management. Traditional engineering approaches seek operational stability. Emerging approaches for resilience planning consider how complex, interacting systems change and evolve in predictable and unpredictable ways. Ecological resilience describes how disturbances can push a system to a new operational state. While water infrastructure systems are managed to operate within specific cost-effective norms, Chapter 5 described how, with significant disturbances, system costs for water delivery can dramatically increase. Ecological resilience recognizes how multiple factors can compound and create non-linear effects. In operations research, multi-objective optimization provides improved tools for planning in systems with multiple, potentially-competing goals and potentially non-linear responses. Infrastructure planning that emphasizes resilience (either engineering or ecological) will increasingly incorporate risk assessment, climatic uncertainty, and the potential for broad system changes from unpredictable events. Resilience is broadly used in planning and policy precisely because it can address uncertain threats that cities face from sea level rise, capital shortages, and resource scarcity. It serves as a useful heuristic across fields to describe policy goals for “bouncing back” to either the same or new systems.

2.2 Methodological Contributions

The chapters of this dissertation include several novel models and analysis approaches that provide methodological contributions to water resources and urban water management.

First, the integrated model for metropolitan-scale stormwater management presented in Chapters 3 and 4 is novel by combining the technical, economic, environmental, and regulatory factors that influence cost-effective system development. In addition, the model identifies the role of urban environmental processes as a core driver of system design and synthesizes design considerations across a variety of city types.

Second, Chapter 4 extends the metropolitan stormwater model with a risk-based approach to planning, which contributes a wholly new approach to existing literature in stormwater management that emphasizes design targets.

Third, Chapter 5 applies the concept of ecological resilience and presents a model to show how water resource systems are a function of past and current decisions. Significant changes in the structure and function of systems may result from large disturbances, and planners must better incorporate such planning approaches in future decades with greater environmental variability. The chapter also ties the concept of ecological resilience with recent research in multi-objective modeling and planning for water resources.

Finally, Chapter 6 is the first detailed analysis of network theory applications in a large-scale model of a water resource system. It is also the first research to link analysis techniques from complex networks and systems with a water resource network model, which connects water infrastructure systems with broader encompassing theories of the structure and function of networks. As such, the chapter is novel in characterizing a large-scale water resource network not as a wholly-planned system, but instead as one example in a larger collection of networked systems, which surround and fuel human life.

3 Further Research

Cities, and the infrastructure systems that run them, have both planned and unplanned aspects. The planned aspects create the order we recognize today. Planning improved health, safety, and organization in industrial-era cities of North America, Europe, Asia, and Australia. The unplanned aspects emerge from the collective decisions and unrecognized constraints that rule how people interact with each other and infrastructure systems connect and function. The majority of future urban development at the global scale lies in growth that is less-controlled through central planning but still subject to physical, social, and environmental constraints.

For water resource systems in cities, this reality could lead to new planning insights. As many urban water systems will likely integrate distributed technologies in coming decades, water planners can shape future systems by not only planning how the system will function, but also by crafting how individuals make decisions to improve the collective performance of the system. Regulations, economics, and education are all important in this regard. In addition, analysis approaches stemming from the study of complex systems, including agent-based models and evolutionary computing, may be useful in a world that recognizes the intricacy of related systems. An irreversible, probability-driven universe may even be a fundamental component of our understanding of the physical world (Prigogine 1997). At the same time, some tools from this realm of complex systems modeling, such as agent-based simulations and genetic algorithms, are based on highly simplified conceptions of real-world processes (person-to-person interactions or gene transcription) and may fail to capture uncertainty for planning. Simple models and analysis techniques can still identify core insights when well constructed, while new methods are needed to incorporate adaptability into infrastructure design. Risk, networks, and environmental planning will all be important aspects of developing the next evolution of water infrastructure.

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