The Water Environment of Cities

Lawrence A. Baker
Editor

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Preface

The concept for the *Water Environment of Cities* arose from a workshop "Green Cities, Blue Waters" workshop held in 2006.[1] The workshop assembled experts from engineering, planning, economics, law, hydrology, aquatic ecology, geomorphology, and other disciplines to present research findings and identify key new ideas on the urban water environment. At a lunch discussion near the end of the workshop, several of us came to the recognition that despite having considerable expertise in a narrow discipline, none of us had a vision of the "urban water environment" as a whole. We were, as in the parable, blind men at opposite ends of the elephant, knowing a great deal about the parts, but not understanding the whole. We quickly recognized the need to develop a book that would integrate this knowledge to create this vision. The goal was to develop a book that could be used to teach a complete, multidisciplinary course, "The Urban Water Environment", but could also be used as a supplemental text for courses on urban ecosystems, urban design, landscape architecture, water policy, water quality management and watershed management. The book is also valuable as a reference source for water professionals stepping outside their arena of disciplinary expertise.

The Water Environment of Cities is the first book to use a holistic, interdisciplinary approach to examine the urban water environment. We have attempted to portray a holistic vision built around the concept of water as a core element of cities. Water has multiple roles: municipal water supply, aquatic habitat, landscape aesthetics, and recreation. Increasingly, urban water is reused, serving multiple purposes. In this vision, humans are not merely inhabitants of cities, but an integral part of the urban water environment. Humans alter the urban hydrologic cycle and the chemical and physical integrity of urban water systems and are recipients of these alterations. Some of those changes are beneficial, like being able to enjoy a well-planned park with water features whereas others are harmful, like exacerbated flooding caused by poorly planned development upstream. These changes alter the sustainability and resilience of cities in ways that can reasonably be predicted, or at least, anticipated.

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[1] Novotny, V. and P. Brown, 2007. Cities of the Future: Towards Integrated Sustainable Water and Landscape Management. Proceedings of an international workshop held July 12–14, 2006 at the Wingspread Conference Center, Racine, WI. IWA Publishing, London.

To reach a multidisciplinary audience, we have written the book for a scientifically literate audience – a reader with a B.S. degree but who would not necessarily have specialized education in hydrology, engineering, law, or other topics. We used several techniques to achieve this goal. First, we explored the same six cross-cutting themes in each chapter – water scarcity, multiple uses of water, water management institutions, integration of new knowledge, sustainability, and resilience. Key paradigms from our specialties, which both guide and limit us, are explained to build context for each chapter. Third, we tried to limit specialized jargon to the extent possible. When specialized terms are needed to achieve precision of meaning, they are defined and included in a glossary. Chapters were cross-reviewed by chapter authors from other disciplines to assure that chapters are readily understood by readers from other disciplines. Finally, last chapter is a synthesis, developed in a workshop held in January 2006 at the Riverwood Inn in Otsego, Minnesota, after authors had written their core chapters.

Minnesota, USA Lawrence A. Baker

Acknowledgments

We would like to thank Vladimir Novotny for organizing the Green Cities, Blue Waters Workshop, a project that has catalyzed thinking about urban water and has led to several ongoing, interrelated projects. I would like to thank several people for making the synthesis workshop a success. First, I thank two discussants who aptly guided us in our search for synthesis: Lance Neckar, from the University of Minnesota's Department of Landscape Architecture, and Joan Nassauer, a landscape architect in the School of Natural Resources and the Environment at the University of Michigan. I would also like to thank Jana Caywood, a graduate student at the University of Minnesota, who did an extraordinary job organizing the logistics of the workshop, as well as contributing perceptions of a sociologist to the synthesis discussion. Finally, I would like to acknowledge support from the National Science Foundation for supporting the synthesis workshop and related activities (award CBET 0739952 to the University of Minnesota).

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Cliff Aichinger is currently the Administrator for the Ramsey-Washington Metro Watershed District, a watershed management organization in St. Paul, Minnesota. Under his leadership, the District has completed three Watershed Management Plans, lake studies, TMDL studies, development rules, and more than $30 million in capital improvements. He has had over 35 years experience in water management and environmental planning in Minnesota and has held positions at local, regional and state levels of government. Cliff has also been involved in a number of state and national committees and studies evaluating water management science and institutional structure. He was a member of the National Research Council team that authored “New Strategies for America’s Watersheds”. He has a B.S. from the University of Minnesota.

Lawrence A. Baker, Ph.D. (Editor), is a Senior Fellow in the Minnesota Water Resources Center and owner of WaterThink, LLC. His research examines human ecosystems, at scales from households to urban regions, with the goal of developing novel approaches for reducing pollution that are more effective, cheaper and fairer than conventional approaches. Recent research has included development of phosphorus balances for watersheds of recreational lakes, examination of drivers change in water quality, source reduction for storm water pollution, the role of human choice on generation of pollutants through households, and nutrient flows through cities and farms. He has published more than 100 technical publications and one book, “Environmental Chemistry of Lakes and Reservoirs”. He was a primary technical contributor to the *Integrated Assessment*, the final report of the National Acidic Precipitation Assessment Program to the U.S. Congress, and chaired the Human Health Committee of the Arizona Comparative Environmental Risk Project, which produced a “blueprint” for future environmental initiatives in Arizona. He writes articles and columns for the popular press, including the *Minneapolis Star and Tribune* and the *Minnesota Journal*.

Brian P. Bledsoe, Ph.D., P.E., has 20 years of experience as an engineer and environmental scientist in the private and public sectors. He is currently an Associate Professor in the Department of Civil and Environmental Engineering at Colorado State University. His research and teaching interests are focused on the interface between engineering and ecology with emphasis on multi-scale linkages between land use, hydrologic processes, sedimentation, channel stability, and water quality. Prior to entering academia, he served as Non-point Source Program Coordinator for the State of North Carolina. He has authored over fifty publications related to stream and watershed processes, restoration and water quality, and is a licensed professional engineer in NC and CO.

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John Crittenden, Ph.D., P.E., is the Richard Snell Professor of Civil and Environmental Engineering at Arizona State University. His areas of expertise include sustainability, pollution prevention, physical–chemical treatment processes in water, nanotechnology synthesis and environmental applications and implications, and catalysis. Dr. Crittenden has more than 120 publications in refereed journals and 135 reports, or contributions to proceedings, 4 copyrighted software products and three patents in the areas of pollution prevention, stripping, ion exchange, advanced oxidation/catalysis, adsorption and groundwater transport. In 2005, Dr. Crittenden coauthored the book, “Water Treatment Principles and Design” (1984 pages and 22 chapters), which has been recognized as the most authoritative text on theory and practice of water treatment. He has acted as a consultant to over 100 utilities, companies, and universities, worldwide on air and water treatment, sustainability science and engineering, and pollution prevention since 1975. For his contributions to water treatment theory and practice, Dr. Crittenden was elected to the National Academy of Engineering in 2002. Dr. Crittenden is an Associate Editor of “Environmental Science & Technology”.

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Kristina Hill is a Professor of Landscape Architecture and Urban Design at the University of Virginia. She received her doctoral training in design and ecology at Harvard University, and taught urban design at the Massachusetts Institute of Technology and the University of Washington in Seattle before joining the UVA faculty. Kristina has served as a professional consultant on urban design, infrastructure and water for states and municipalities in the U.S. and Germany, as well as for private sector development clients. She edited the book “Design and Ecology” (Johnson and Hill, Island Press, 2002), and is about to release a book on case studies of urban ecological design and water with the University of Washington Press. Her current focus is on the relationship between urban design and the health of near shore marine ecosystems.

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Chapter 1
Introduction

Lawrence A. Baker

1.1 The Water Environment of Cities

Few of us, even among professionals who think about specific aspects of water every day, have ever thought about the "water environment of cities". What does this mean, and why is it important? Some aspects may be familiar, whereas others are out of sight, and others are conceptual constructs. Parts of the urban water environment are obvious. Water features are often the heart and soul of many cities. Chicago's Lake Michigan shoreline, the Chain of Lakes park system and the Mississippi riverfront in Minneapolis (Fig. 1.1), and Boston's "Emerald Necklace" define these cities and make them uniquely livable. These water features renew the soul.

Water also contributes to the economic lifeblood of a city. Most coastal cities are located at the mouths of large rivers and have deep harbors. Early industrial cities were often located on rivers, which were used to provide both hydro-based energy and transportation. In an earlier era, most freight was moved by water. Even today, ports that transport three-fourths of our international trade (on a tonnage basis) dominate the shorelines of coastal cities. As we will see, the decline of inland waterway transportation has led to a major transformation of the urban waterfronts, now dominated by parks and housing. Water was also the dominant form of energy for early industrialization, spurring the growth of hundreds of small cities on high-gradient rivers prior to the advent of economies based on fossil fuels.

A less obvious part of the urban water environment is the municipal water supply system, which brings water from outside a city's boundaries, treats it, and distributes it throughout the city via a subterranean network of pipes. Much of this water becomes wastewater, which flushes human and industrial wastes out of the urban core via an extensive network of underground sewers. These sewers once emptied directly to rivers but now nearly always discharge wastes to sophisticated wastewater treatment plants, often capable of digesting 95% of the organic waste before discharging relatively pure water into rivers.

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Fig. 1.1 An urban riparian environment: the Mississippi River as it flows through Minneapolis. Source: National Park Service - Mississippi National River and Recreation Area

Cities have entirely different hydrologic environments than the natural environments they replaced. Precipitation that once infiltrated into forest or agriculture soils becomes surface runoff when the impervious surfaces of cities (roads, driveways, parking lots, and rooftops) replace pervious, vegetated landscapes. Storm sewers in urban *watersheds* drain impervious surfaces, transporting water very quickly to urban streams, lakes, and rivers. The hydrology, morphology, and aquatic biota of streams are severely altered by urbanization, transforming them into clearly distinguishable "urban" streams when approximately 10%–20% of the watershed area becomes covered with impervious surface (Booth et al. 2002).

Even further below the surface than storm sewers (usually!), there may be large underground groundwater *aquifers*. These are often used for water supply, and sometimes for waste disposal, and sometimes for both. Overuse of aquifers not only depletes them, but can cause land to subside and fissure, damaging urban infrastructure. In coastal areas, overdraft of groundwater results in seawater intrusion.

Cities also include important aquatic ecosystems. Fifty years ago, rivers downstream from cities were often grossly polluted with untreated sewage, often creating "dead zones" of severely oxygen-depleted waters. Many of these have been restored to be *fishable and swimmable*, sometimes providing excellent angling within view of skyscrapers. Some types of wetland ecosystems are so valuable to urban dwellers that mere proximity to them increases residential property values (Boyer and Polaksy 2004). The ecosystems of urban lakes and reservoirs used to store municipal source water are particularly important, because eutrophication caused by encroaching urbanization can greatly impair the quality of drinking water, especially through the production of taste and odor compounds by blue-green algae.

Most importantly, the urban water environment includes humans! Water features in the urban landscape – whether natural streams and lakes or constructed fountains – restore body and mind and help create our "sense of place" (*place identity*) in the world. In studies of landscape preference, subjects nearly always indicate preference for landscapes with water features (Ulrich 1993). Desirable landscapes not only are preferred but may have actual restorative properties, including improvement of higher order cognition. One study suggests that a view of open water might speed up the recovery from open heart surgery (Ulrich 1993).

Finally, we cannot conceptualize the water environment of cities without consideration of the legal and institutional systems that shape our biophysical world and provide connections to larger political systems. In fact, as we will see, many urban regional institutions developed partly, and some exclusively, to manage various aspects of the urban water environment.

The water environment of cities includes all of these things, but more importantly, it is the whole of these things – a vast, interconnected system of human nature. Yet, even after 200 years of industrial urbanization, water management tends to focus on individual parts of the urban water environment, not the whole. For example, we know that new development which adds impervious surface increases flooding downstream, but flood policy mainly focuses on amelioration of flood effects in downstream communities. Stormwater pollution management focuses mainly on treating stormwater after it enters a storm sewer, rather than prevention of pollution in the first place. Recycling wastewater, a well-intended water conservation effort, can accelerate accumulation of salts in desert cities, with poorly understood consequences. Our policies to manage water and pollution are often fragmented, dealing with one part of the picture. Policies have major gaps, and are sometimes even antagonistic, working at cross-purpose with other policies.

The overarching goal of this book is to develop a holistic view of the urban water environment, in order to manage it more effectively. There are two key reasons for doing this now, one a problem and the other an opportunity. The problem is that we have major urban water problems that cannot be solved using conventional, compartmentalized thinking. These problems are becoming more severe as urban populations swell, high-quality source water becomes scarcer, demands for environmental quality increase, and climate change brings new uncertainties into play. New thinking is needed to yield solutions that are cheaper, more effective and fairer. Second, we are at a moment in history with unparalleled opportunity: our emerging information technologies. Our ability to acquire, store, and process data is accelerating exponentially, enabling entirely new ways of creating and using knowledge to improve management of water resources. These new ways of thinking and new technologies can bring the concept of "design with nature", envisioned nearly 40 years ago (McHarg 1971), to fruition.

The next section is a brief history of the water environment of the modern city, from which we can learn several key themes that will help us to look into the future. We then identify six cross-cutting themes which are developed throughout the book.

1.2 A Brief History of the Urban Water Environment

1.2.1 Advent of the Industrial City

The pessimistic reader might be suspicious of our goals from the outset. Aren't governments bound to be incompetent? Doesn't the Katrina disaster illustrate how poorly we have prepared for water-related disasters? Isn't Atlanta a case study in the failure of urban water supply management? Aren't Phoenix and Las Vegas poised for catastrophe, as water demand outstrips water supply? What new knowledge and new concepts have evolved that would allow us to manage our urban water environments in a fundamentally sounder fashion than we have in the past?

The history of the water environment of the modern, industrialized city reveals more complex, nuanced view of human progress. Although the cities with a million or more people existed more than a thousand years ago in warm climates (Baghdad was the first with over one million, in 800 AD; Chandler 1987), the industrialized city of the North Temperate Zone is a relatively modern institution in human history. London was the first of these, attaining the one million mark in 1810 (Fig. 1.2). Modern urbanization was made possible by industrialization, which in turn was driven by two parallel, symbiotic developments: coal mining and the development of the steam engine, which in turn enabled more intensive mining. By 1800, London desperately needed a new source of energy to augment dwindling forests and found it in the mines of Newcastle-on-Tyne, readily accessible by ocean transport (Freese 2003). During the 19th century, London's population grew nearly 8-fold, propelled by a 15-fold expansion in energy use, supplied mainly by coal. Growth in cities on the eastern coast of the United States lagged that of London, but then took off with a vengeance: Philadelphia grew 20-fold during this period and New York grew nearly 70-fold since the early 19th century (Fig. 1.2). From 1800 to 1975, the cumulative population of the world's ten largest cities increased 20-fold.

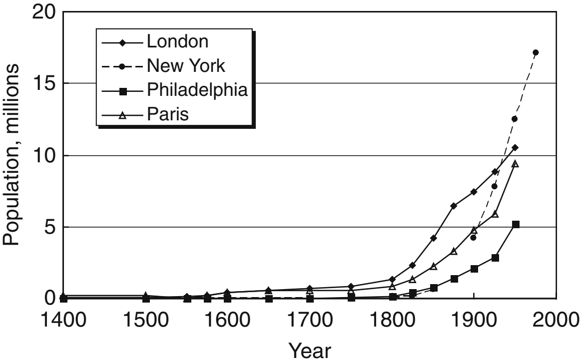

Fig. 1.2 Population growth of key cities during industrialization

1.2.2 Evolution of Modern Water and Sewage Works: The London Experience

Halliday (2001) reviewed the early development of London's modern water and sewage systems. In London, water was brought into the city since Roman times, augmented by many public wells. The average person hauled water from distribution points, whereas wealthier citizens employed the service of water carriers. London and other cities had developed extensive drainage systems by the early 19th century, often built to follow natural streambeds. But these were designed originally to convey only rainwater and urban drainage, not household sewage. At the beginning of the 19th century, the standard practice for urban sanitation was to dump excrement into latrines and cesspools – basically pits for storing human feces. London had about 200,000 cesspools in 1810. Human manure was considered an important agricultural resource, collected by "nightsoil men", who hauled human manure to farms, a practice that was continued in Beijing, China until 2000 (Browne 2000). The Romans had well-developed sanitary sewer systems and even limited household sewage disposal (only for the very wealthy, of course), but the idea of conveying sewage through underground pipes fell out of the public mind until the mid-19th century.

Widespread adoption of the water closet – the precursor to the modern flush toilet – changed that. As one might expect, water closets were very popular, and by 1850 there were about 250,000 water closets in London. Cesspools of the time were not designed to handle the higher flows; hence they overflowed, creating a stinking mess. One can only imagine a London gentleman, the proud owner of his new water closet, stepping off his porch into the stinking mire of an overflowing cesspool, first in shock (&%$#@!), and then having a hydrologic Zen moment. To compound the problem, the value of human manure declined for several reasons. First, as London grew, it became more expensive to haul manure to more distant agricultural fields. Simultaneously, England farmers began importing newly discovered South American guano for fertilizer, and they became more proficient in cultivation of legumes, which replenished nitrogen to soils (Smil 2001).

By the mid-1800s London's sewage situation had become dire. Four cholera epidemics occurred between 1800 and 1860. The prevailing wisdom, which maintained that cholera was spread by foul air, a theory known as the "miasmatic" theory, prevented Londoners from taking straightforward action until the mid-19th century, when Dr. John Snow and other epidemiologists gradually accumulated evidence that cholera was spread by contaminated water, not air. This cleared the way for Parliament to pass the "Cholera Bill" in 1845, which mandated that all new and existing buildings be connected to the existing storm sewers. Parliament also formed the Metropolitan Commission of Sewers in 1848, which compiled a series of reports and plans for dealing with the growing sewage problem and the Metropolitan Board of Works in 1955 – the precursor to modern regional urban sewage authorities.

As is often the case, the solution to one problem (filth in the streets) often creates another problem. In this case, the Thames River, which received most of London's new sewage, became so polluted from the new discharges of sewage that the stench forced Parliament, located on the banks of the Thames, to adjourn! The “Great Stink”, as the 1858 event became known, motivated Parliament to provide the funding for an extensive renovation of its sewer system, which eventually led to the disappearance of cholera (Halliday 2001).

1.2.3 Urbanization and Water in the Eastern United States

The pattern of development of urban water supply systems in the United States reflected a strong sense of individualism, which delayed the construction of public waterworks in many cities until the 1870s (Ogle 1999). Many households relied on rain cisterns, local wells, and small water companies for water supply. Early public water systems were often “segmented”, supplying water only to neighborhoods that could pay for them, meaning relatively the wealthy ones. Philadelphia constructed the first municipal water system in the United States in 1802, but even as late as 1880 there were only 598 public water systems in the United States (Tarr 1996). As public water systems and indoor plumbing became widespread, water use increased dramatically, exacerbated the sewage problem as it had done in London. A curious transformation of U.S. water systems occurred after the mid-19th century, with nearly all major cities eventually adopting public water supply systems to virtually all households, at minimal cost. Even today, nearly all major cities in the United States have publicly owned, and mostly publicly operated, water supply systems which provide universal service.

On the downstream side, nearly all larger U.S. cities (except New Orleans) decided to discharge sewage into existing storm sewers rather than create separate “sanitary” sewers (Tarr 1996). No U.S. city had human sewage disposal systems by 1850, though most developed them between 1850 and 1900. Baltimore was the last U.S. city to build a sewer system, only after a fire destroyed much of the city in 1904, catalyzing the need for new infrastructure (Boone 2003).

The provision of sewage treatment occurred even later. Rudimentary sewage treatment by land application was the main sewage treatment technology of the late 19th century. Sewage treatment was particularly important in the United States because many cities were located downstream from other cities; hence their water intakes were subject to contamination by sewage produced upstream. The engineering community of the era developed a consensus in the late 1800s that sewage treatment was not economically justified because dilution and natural purification would be adequate (Tarr 1996). Downstream *water treatment plants*, it was reasoned, could then further purify the water using sand filtration, first used in London in 1827. Data compiled by Tarr (1996) suggested that adoption of sewage collection, with no provision for treatment, may have increased typhoid mortality rates in several cities, presumably by diffusing the typhoid bacterium downstream.

The first century of urbanization did not go well from a public health perspective. By 1890 there was a substantial “urban penalty” for urban living: Mortality rates in U.S. cities were 30% higher than in rural areas (Culter and Miller 2005). The displacement of the miasmatic theory by the germ theory of disease following breakthroughs by Koch and Pasteur in the late 1800s provided a solid theoretical basis for new practices in clean water technology. Chlorination became a key water treatment process, first started in Jersey City in 1908 and becoming nearly universal for major U.S. cities within a decade (Culter and Miller 2005). Chlorination also became widely used to treat sewage, which together with primary treatment of sewage (simple sedimentation), greatly reduced the discharge of human pathogens to rivers and other waterways.

Treatment of drinking water in water treatment plants by filtration and chlorination, cessation of discharges of wastewater near water treatment plant intakes, and exploitation of new and cleaner source waters greatly improved the quality of urban life in the early 20th century. Typhoid mortality dropped precipitously, to near zero levels by the 1940s. Life expectancy increased from 43 years to 63 years; clean water (treatment of water and wastewater) accounted for nearly half (43%) of the improvement (Culter and Miller 2005). When the *British Medical Journal* polled its readers to determine what they thought were the most important medical advances since 1840, the winner was "sanitation" (clean water and sewage disposal; BMJ 2007).

Cities continued to discharge untreated, or minimally treated, sewage for many more years. Cities in the United States were largely sewered by 1940, but only 57% of sewered areas had sewage treatment (Tarr 1996). The discharge of raw sewage grossly polluted rivers, often causing oxygen depletion and fish kills, and little had been done to curb industrial pollution. The wake-up call occurred in 1969, when *Time Magazine* showed the Cuyahoga River burning (Fig. 1.3). In reporting the story, *Time Magazine* described the river as "chocolate-brown, oily, bubbling with subsurface gases, it oozes rather than flows".

The Cuyahoga River fire was a catalyst for passage of the Clean Water Act in 1972. The Clean Water Act had a major impact on urban water, mandated specific water quality standards for rivers, establishing treatment standards for both

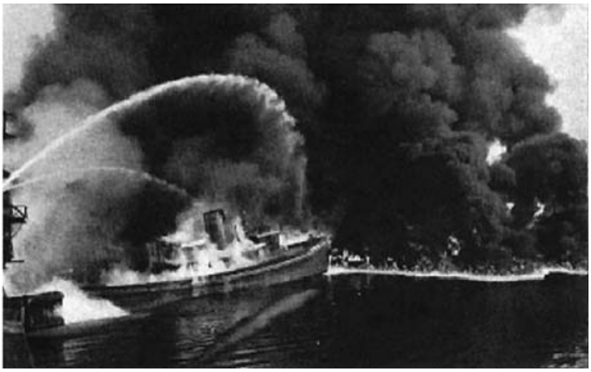

Fig. 1.3 The photo of the Cuyahoga River on fire which appeared in the August 1, 1969 issue of *Time Magazine*. Reprinted with permission from AP Photos

industrial and municipal wastewater treatment, requiring the pre-treatment of industrial wastes discharged to sewers, and providing cost-sharing for the construction of municipal *wastewater treatment plants* throughout the country. By the late 1990s, the organic loading of municipal wastewater had declined by 45% even while the U.S. urban population increased by nearly 50% (USEPA 2000). This decreased the number of oxygen-depleted dead zones below cities and allowed the resurgence of fish populations. Since 2000, the new thrust in reducing urban water pollution has been improved management of urban runoff.

1.2.4 Energy and Water Transportation

Early industrialization, water was a major source of energy and route of transportation for growing cities. Most large cities were coastal ports and many smaller industrial towns were located on high-gradient rivers which provided hydraulic energy. Heavy freight was moved on water whenever possible (Smil 1994). For example, the steel industry of Pittsburgh relied on the Ohio, Monongahela, and Allegheny Rivers to ship coal and ore to the city and finished steel from the city. As railroads expanded during the last half of the 19th century, some cities served as connecting points for rail and water transportation. Chicago is perhaps the best example. Railways connected Chicago to the east and west and waterways connected Chicago to the north (Lake Michigan and the St. Lawrence Seaway) and south (the Chicago Canal and the Mississippi River) (Cronan 1991). In the 20th century, railways became the dominant movers of freight in the United States. By 2000, railways dominated U.S. domestic transportation, accounting for 42% of ton-miles. Trucks accounted for another 28% of ton-miles, whereas water transportation accounted for only 13%. However, water is still the dominant form of international freight transport, carrying about three-fourths of the tonnage, and port cities on ocean fronts still maintain their water transportation function.

Urban waterfronts, once the hub of commercial life of many cities, declined through the first half of the 20th century. Even where shipping remained important, older port areas were supplanted by larger, modernized ports that could handle larger ships and larger cargoes, generally located downstream of the original ports (Marshall 2001). The trend toward decline was reversed about 40 years ago with urban renewal that converted decaying ports into thriving commercial and residential centers. One key factor in this resurgence was the environmental cleanup of rivers, driven by improved municipal and industrial wastewater and by the cleanup of old industrial “brownfields”. Urban waterfronts exemplify the concept of succession in urban systems, an analog to succession in natural plant communities (Fig. 1.4).

The changing role of water in energy and transportation also affected smaller, upstream industrial cities. During early industrialization, prior to the widespread use of fossil fuels, hydropower was a major source of energy for small factories and mills. Because this power was often provided by small, low-head dams, many

Fig. 1.4 Transitions of an urban waterfront. The St. Paul riverfront, seen from the Wabasha Bridge, in 1930 (*left*), and in 2008. The earlier photo shows multiple rail lines along the shore, and buildings on the bluff, with no visible landscape amenities. A single rail line remains in 2008, along with a tree-lined boulevard, but a pedestrian walkway overlooks the river, and a park has been built on the bluff. The 1930-era photo with permission from the Minnesota Historical Society; the 2008 photo was taken by the author

small industrial cities located on high-gradient rivers far upstream from the mouths of rivers flourished and grew. As coal (and later other fossil fuels) became available, hydropower fell out of vogue. Many of these cities declined, at least temporarily, and hundreds of small dams that were once critical to small cities fell into disuse. Many of these focal points of local cultures are now being torn down to avoid the cost of structural repairs and to restore the natural course of rivers. In Wisconsin alone, more than 100 small dams have been removed, many of which were once central to the economy of the towns in which they were located. Perhaps in the coming years of energy scarcity some of these cities will restore or rebuild some of these dams to again provide hydropower.

1.2.5 Water and Urbanization in the Arid Southwest

Most cities in the temperate regions of the United States were built without severe constraints on water supply. The situation was very different in the arid southwestern United States as cities started to develop in the mid-20th century: Water was a critical issue from the very start. The difference can be represented by comparing water footprints – the size of watershed needed to provide water for a single person. For New York City, where precipitation is about 40 inches per year, the water footprint is about one-third of an acre. By contrast, residents of Phoenix, Arizona use 2.5 times more water per person (the higher use is mostly due to landscape irrigation) and local rainfall is only seven inches. The resulting water footprint for a Phoenix resident is four acres – 13 times larger!

Southwestern cities like Phoenix, Los Angeles, Denver, and Las Vegas rely on spring runoff that originates from snowmelt at high elevations and is stored in large reservoirs. They may also utilize water conveyed across watershed boundaries. For example, San Diego gets much of its water from the 240-mile Colorado River Aqueduct, which transports water from the Colorado River. Flows in the Colorado River above the point where water is diverted to the Colorado River Aqueduct are maintained by a series of major dams upstream on the Colorado River and numerous smaller dams located on tributaries.

Building the huge dams that supply water to southwestern cities depended on massive federal subsidies, guided by a once-massive federal agency, the Bureau of Reclamation, in the early 1900s. The initial motivation for most of these dams was not urban development, but agricultural development, part of a broad policy to encourage farmers to settle in the American West (Reisner 1993). From 1908 onward through the 1970s, the bureau eventually built 345 dams. Several factors affecting rapid urbanization of southwestern cities were (1) expansion of railroads and highway as key movers of people and freight, (2) the invention of air conditioning, (3) availability of "water rights" that accompanied farmlands sold for urban development, and (4) constraints on the selling price of water imposed by the original water utility charters that kept water prices far below market value. To augment the highly subsidized surface water, most cities also withdrew freely from *groundwater* aquifers, often dropping the level of the aquifer by hundreds of feet. Moreover, these cities have often literally sucked rivers dry, resulting in severe damage to downstream aquatic ecosystems.

1.2.6 Flooding

Urbanization drastically alters the hydrologic cycle of a watershed, as we will see in Chapter 2. One of the most important aspects of altered hydrology is increased flooding. Cities both cause floods and are impacted by flooding, often being located on the banks of waterways to take advantage of waterborne transportation. A city can cause downstream flooding by increasing the percentage of impervious surface – surfaces such as roads, rooftops, and parking lots, by filling wetlands, resulting in loss of water storage, and by increasing the drainage density through the installation of storm sewers. In many urban regions, increased flow from upper parts of the watershed has increased flooding in downstream parts of the watershed (Konrad 2003).

Throughout the first half of the 20th century, the main responses to urban flooding were the construction of flood control reservoirs upstream, increased drainage to route water downstream as quickly as possible, and the construction of levees to keep flood flows within riverbanks. Still, many cities along major river basins in the eastern United States periodically flooded. I happened to grow up in one of these towns, New Martinsville, West Virginia, on the banks of the Ohio River. The downtown area flooded so regularly that there was a local law requiring that motorboats cruising on Main Street not exceed 15 miles per hour – a law intended to minimize breakage of shop windows!

Since 1968, the Federal Flood Insurance Act has limited the types of buildings that can be insured on flood plains, allowing only those that can withstand periodic flooding without damage. Since then, historical commercial and residential districts located in frequently flooded areas near rivers have gradually been moved uphill and have been replaced with parks and other land uses that can withstand flooding with minimal damage. A more recent development has been to "soften" urban landscapes, reducing the amount of impervious surface and building stormwater ponds, wetlands, swales, and other *best management practices* (BMPs) to limit the deleterious impact of urbanization. Many municipalities and other local units of government now require that new developments retain a specified amount of precipitation "on site", storing it in ponds or infiltrating it to groundwater in infiltration basins. Some planners and hydrologists envision creating low-impact development designs that nearly mimic natural hydrologic conditions.

1.3 Summary

This brief history offers several insights regarding the urban water environment.

1. *Urbanization often occurs very quickly*: Rapid urbanization often overwhelm the ability of local municipal governments to evolve new water management systems quickly, leading to water crises. London was unable to respond adequately to its urban water crisis until the Metropolitan Water Board was formed. The formation of water management institutions is often needed to avert crisis during urbanization.
2. *Progress often has unintended, unpleasant consequences*: The widespread adoption of water closets in London without provision for managing the excess water entering cesspools is a classic example. Downstream flooding caused by upstream development, industrial pollution, and depletion of urban aquifers are other common, unintended consequences of urbanization.
3. *Crisis drives innovation*: Epidemics of cholera and typhoid spurred scientific advances in epidemiology and microbiology during the 19th century, which led to improved water sanitation, one of the most important scientific advances of modern civilization. Some of this innovation is positive, irreversible cultural evolution – gains in wisdom that will be transmitted through generations.
4. *Management of the urban water environment has lacked holism*: Most cities manage discrete parts of their water environments, such as wastewater or water supply, but rarely connect the parts. Very few cities are managed using complete hydrologic balances. We are starting to tie pieces together – like reducing downstream flooding through changes in upstream land use practices – but we are not very far along in understanding and managing this holism.
5. *The urban water environment will continue to evolve*: This evolution reflects broader economic, technological, and social change.

1.4 Looking Forward

The central premise of this book is that we can improve the quality of urban life by thinking more holistically about the urban water environment, incorporating ideas from hydrology, engineering, planning, law, and ecology to develop a view of the "urban water environment" as a central organizing concept for cities.

1.4.1 The Magnitude of the Problem

Urban regions throughout the world are gaining population, placing increasing pressure on water resources. Metropolitan areas in the United States have been growing at a rate of about 1% per year since 1960. Continued growth at this rate would result in 65 million more urban dwellers by 2030, a 30% gain. Throughout the world, half of the world's population (some 3.2 billion people) are now living in cities, and the urban population is expected to swell to nearly 5 billion by 2030 (Table 1.1). Nearly all of the world's population growth will be in cities in less developed regions of the world, where poverty and corruption often stand in the way of developing appropriate water infrastructure.

As urban populations increase, and particularly where this expansion is also accompanied by gains in average wealth, water supplies often become strained, especially in arid lands, where urban needs and agricultural needs compete. Many cities in the southwestern United States already have severe problems with long-term water supply, as do some cities in wetter regions, such as Atlanta and Miami. Many U.S. cities will also have to replace water infrastructure within the next few decades, requiring increases in utility fees to a level that may strain budgets of low-income families (CBO 2002).

Downstream impacts of urban drainage remain a serious urban water problem 35 years after passage of the Clean Water Act. Urban stormwater is badly polluted with sediments, nutrients, metals, and salts. In some cases, these pollutants accumulate within urban systems, contaminating groundwater and soils. Moreover, the hydrology urban streams have often been severely disrupted, aggravating downstream flooding and damaging aquatic habitats.

Finally, water-related policies are often fragmented, outdated, and ineffective. "End-of-pipe" solutions that worked well to treat municipal sewage don't

Table 1. World's projected urban population growth, 2005–2030, in billions

	2005	2030	Percentage of change
World	3.15	4.91	56
More developed regions	0.90	1.01	13
Less developed regions	2.25	3.90	73
Less developed, as %	71	79	–

Source: U.N. (2006)

necessarily work to reduce pollution in urban stormwater or to improve hydrologic conditions. Although some institutions have emerged that match watershed boundaries (surface drainages or groundwater basins) and have broad mandates, urban water environments are generally managed by a mish-mash of agencies and governmental units, each with narrow agendas.

1.4.2 Cause for Hope

In a sense, the glass is half full. The history of the urban water environment has shown that out of crisis comes innovation and renewal. At present, an obvious innovation is the enormous advances in information technologies – the 1000-fold increase in computing speed over the past 10 years, with parallel improvement in the quality of satellite imagery. These advances allow great technological advances. For example, we are now starting to use sophisticated mathematic models rather than statistical analysis of historical records to forecast flooding, and we are developing whole new ways of communicating hydrologic knowledge to policy makers and even ordinary citizens. These advances in information technology are comparable with the invention of the steam engine that spearheaded the Industrial Age or the discovery of germ theory that led to innovations such as water treatment and vaccination that rapidly increased lifespan in the early 20th century. We are therefore hopeful that this book does not merely lead to incremental improvements in managing urban water environments, but serves as a prolegomenon for a new paradigm of environmental management, to be fully developed by our readers in the next few decades..

1.4.3 Cross-Cutting Themes

To build coherence across a variety of topics, we developed each chapter on the same six cross-cutting themes. The first is *water scarcity*. All other policies regarding urban water are increasingly being linked to the issue of scarcity. To a great extent, we are able to see that urban water scarcity can occur even in regions with ample rainfall. The second theme is *multiple uses of water*. In most locations, urban water supply no longer means simply acquiring source water, using it, and flushing it downstream. In today's urban water environment, urban stormwater might be collected in an infiltration basin and used to recharge depleted aquifers. Suburban streams, once considered little more than conduits for drainage, are now being restored for trout fishing. In coastal areas, management of urban flows and reduction of pollutants is becoming increasingly necessary to maintain economically important finfish and shellfish industries and beach recreation.

The third theme is *water management institutions*. No urban regions have institutions specifically designed to address the entire spectrum of water issues. Management is often based around utilities (regional water supply or wastewater treatment authorities); a few urban regions have strong institutions for management of either surface watersheds or groundwater systems.

As scientists, we implicitly believe that new knowledge will benefit humanity, but our ability as a society to find and incorporate new knowledge into urban design and management is often sluggish. Therefore, our fourth theme is *integration of new knowledge*. New design prototypes can allow development to adapt successfully to new regulatory demands, using new knowledge, and change the ultimate performance of cities as water-using and water-producing systems. The combination of new needs and new opportunities may drive us toward new management models – for example, greater use of *participatory research* and *adaptive management*. There is also a pressing need to integrate the human dimension into transdisciplinary knowledge of human ecosystems. Hydrology alone will not solve our urban water problems.

The final two themes are sustainability and resilience. Using the definition from the Brundtland Commission (U.N. 1987), *sustainable development* ”meets the needs of the present without compromising the ability of future generations to meet their own needs”. In the context of the urban water environment, this includes economic and social environment, as well as the biophysical condition of the environment. The related concept, *resilience*, is the capacity of a system to withstand perturbations without major system changes. In the context of the water environment of cities, these perturbations include droughts and flooding. One specific concern is climate change, which may alter the entire hydrology of a city, creating a whole new set of problems. In addition to “natural” perturbations, there may be perturbations to the built water environment, such as dam collapse or major failures in the water delivery system. Gaining a better understanding of how we can increase urban resilience to these extreme events can help avoid loss of basic services and minimize the damage done by decisions made in crises that ignore medium and long-term consequences.

1.5 Chapter Topics

The first section of this book examines the flow of water and materials through urban systems. In Chapter 2, Claire Welty examines the water budget of cities, developing concepts that will be revisited in several subsequent chapters. Chapter 3, by Peter Shananan, examines a part of the urban water environment that few of us have seen – the groundwater systems that can provide sustenance or wreak havoc, depending on how we manage them. Paul Westerhoff and John Crittenden look at the engineered water environment – our modern water supply, sewage, and stormwater systems – in Chapter 4. Chapter 5 explores the movement of nutrients and materials through cities. Section II focuses on broader uses of the urban water environment. Derek Booth and Brian Bledsoe (Chapter 6) examine the physical and biological structure of urban streams, with an eye towards restoration of urban aquatic habitats. In Chapter 7, Ingrid Schneider looks at the importance of urban water recreation and implications with regard to broader water management. Finally, planner Kristina

Hill integrates many of these ideas into a modern perspective of water in urban design (Chapter 8).

The third section examines legal and institutional aspects of the urban water environment. Robert Adler develops the legal framework that guides urban water management (Chapter 9). The two chapters that follow describe very different types of water management institutions that are used in the eastern United States (Chapter 11, with emphasis on watershed management) and the western United States (Chapter 12, with an emphasis on groundwater basins), written by experienced practitioners who have headed these types of institutions (Cliff Aichinger, Director of the Ramsey-Washington Watershed District in the Twin Cities of Minnesota and James Holway, formerly Assistant Director of the Arizona Department of Water Resources). Finally, William Easter's chapter on economics (Chapter 13) focuses on water pricing and privatization.

After writing the core topical chapters, chapter authors came together to develop a synthesis chapter to integrate their ideas. The last chapter, "Principles for managing the urban water environment in the 21st century", outlines five core principles for water management in post-industrial cities of the 21st century.

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Chapter 2
The Urban Water Budget

Claire Welty

2.1 Basic Concepts

In this chapter our goal is to highlight some of the many ways that urbanization affects the water budget and water cycle. A *water budget* describes the stores or volumes of water in the surface, subsurface and atmospheric compartments of the environment over a chosen increment of time. The *water cycle* has to do with characterizing the flow paths and flow rates of water from one store to another. Understanding how urbanization affects the water budget and water cycle first requires an appreciation of how conditions work in a natural system.

The sun drives the hydrologic cycle, whereby water is evaporated by solar radiation from oceans, inland water bodies and soil, condenses and falls on land as precipitation, and returns to receiving water bodies by either surface runoff or groundwater discharge (Fig. 2.1). There are many critical sub cycles within the overall hydrologic cycle. For example, a portion of precipitation is returned to the atmosphere by evaporation before it reaches the ground. A portion of precipitation that is stored on vegetation (interception storage), on the land surface in puddles (depression storage), or in shallow soil pores, also evaporates rather than moving downward to groundwater or running off to surface water channels. Precipitation infiltrating the soil that is not lost to evaporation can flow downward to *recharge* groundwater, contributing to a rise in the *water table*, or flow shallowly in a lateral direction and discharge to streams. Flow in streams that is not due to surface or shallow subsurface runoff from the land is termed *base flow*; base flow in natural systems arises from deep and shallow groundwater discharging to streams during both storm and non-storm periods.

A water budget or water mass balance can be calculated for any time increment for a chosen *control volume*, where

$$\text{Inflows} - \text{Outflows} = \Delta\,\text{Storage} \tag{2.1}$$

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